VIDEO TAPE RECORDING

JULIAN L. BERNSTEIN

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JOHN F. RIDER PUBLISHER, INC., NEW YORK
a division of HAYDEN PUBLISHING COMPANY, INC.

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PREFACE

The rapid acceptance of video tape recording by the television industry created an urgent and growing demand for information on the subject. Accordingly, in the Fall of 1958 RCA Institutes prepared several courses tailored to meet the requirements and backgrounds of various groups in the industry, both technical and nontechnical. Later, as the outcome of difficulty experienced at that time in finding texts and references on the subject, and the fact that there seemed to be absolutely none available, the author decided to expand the lecture notes used by him as an instructor at RCA Institutes into a book that he believes will be useful to all those working with video tape recorders.

It is the author's conviction that production personnel, directors, editors, cameramen, and others with limited or little technical background, would benefit if they could learn the processes involved in recording video on tape. With this in mind, and because an introductory knowledge of electronics would be needed beforehand, a limited amount of basic theory is given in Chapters 2 and 3. This material begins with waveforms and concludes with color television. Sufficient information has been included to provide the necessary background for the nontechnical reader to understand the descriptions of the machines. In these chapters, as well as in those that follow, explanations and diagrams have been made as simple as possible so that the operations of the recorders can be easily understood. Wherever necessary, photographs have been included to augment the written discussion.

For technicians and engineers, Chapters 10 and 11 contain detailed descriptions and explanations of actual circuits used in video recorders. It is unnecessary to describe in detail video amplifiers, multivibrators, and similar well-known circuits, since excellent treatments on these subjects are readily available. The circuits discussed, therefore, with a few exceptions, are those not commonly found in television equipment, but which are necessary for the correct operation of video recorder machines. In a few instances, well-known circuits that have

been modified to provide more desirable characteristics are also mentioned. The material in these two chapters requires a technical background for complete understanding. Persons lacking such a background may, if they wish, skip them and go directly to Chapter 12. As an added convenience, the circuits discussed in these chapters are referenced in the preceding chapters. Thus, when a circuit is first mentioned in descriptions of the machine functions, the technical reader may refer to the appropriate chapter for a more complete explanation.

Clearly, a book of this type could not have been written without the help of companies and persons who have been active in the field of video recording since its inception. The cooperation of the Ampex Corporation, the Radio Corporation of America, the National Broadcasting Company, Columbia Broadcasting System Inc., and Minnesota Mining & Manufacturing Company in supplying photographs and descriptive material, used with their permission, is gratefully acknowledged. The term VIDEOTAPE is a trademark of the Ampex Corporation, and is used with their permission. Kenneth Herring and Ross Snyder of Ampex, Martin Brill, Jerome Grever, and Anthony Lind of RCA, Robert Thompson and Maurice Artzt of RCA Laboratories, Oscar Wick of NBC, Burbank (Calif.), and Audio Devices, Inc., have all been most helpful and the author is indebted to them. Thanks are also due the author's colleagues at RCA Institutes, particularly to senior instructor Henry Warner, for discussing, reviewing, and criticizing the manuscript.

JULIAN L. BERNSTEIN

Bayside, N. Y.
July 1960

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Chapter 1

INTRODUCTION

When the television revolution erupted immediately after World War II, the pattern of entertainment in America changed radically. People who formerly went out several nights a week now stayed at home to watch the electronic miracle of the day. Within a few years, over 40 million American homes were equipped with receivers, and the television networks were deluged with problems that seemed insurmountable. Some of these problems were not solved until 1956, when the television tape recorder became a practical reality (Fig. 1-1).

East coast, west coast, central or mountain time zones, no matter where you live, you have seen taped programs. Furthermore, unless your local newspaper mentioned it, chances are you were never aware of the fact that the program was recorded, for the technical quality of a taped recording is almost as good as live television.

Television stations, the networks, advertising agencies, even race tracks, are installing recorders as fast as they can get them from the factories. The machines are being used for a variety of purposes, including time zone delay of network programs and prerecording of many shows, both in black and white and color. Syndicated programs, formerly sent out to independent stations on film, are now being recorded on tape. Many branches of the government also find use for the machines.

Television tape recorders offer many operational advantages to their users. One of these is inherent in the recording method, for tape, unlike film, requires no processing. Because of this, the video recorder is able to provide immediate playback after a scene has been shot. It is only necessary to rewind the tape before the results can be seen. Thus, if a director or producer is dissatisfied with a particular scene when a show is being prerecorded, he can order a re-take

while cast and crew are still assembled, instead of having to recall them the next day at added expense (Fig. 1-2). At the race track this same feature permits judges to review a race within 30 seconds after it has been run. An added attraction is the built-in erasing system that wipes the tape clean just

Fig. 1-1. Artist's conception of home use of video recording: the entertainment of the future. With a small tape recorder and a portable TV vidicon camera, TV pictures may be recorded on tape for immediate playback on the family picture-frame TV set. *Courtesy RCA.*

prior to recording. Should a scene be defective in any way, the tape is merely rewound, and a new recording made over the old one.

At this point we might ask why so many programs are being prerecorded on tape. After all, Hollywood produced thousands of movies before the video recorder was developed, and many fine programs are still being produced on film. There is, however, a certain indefinite quality, an intimacy, perhaps, associated with live TV that a filmed program seems to lack. To obtain this elusive characteristic, sponsors insist on live programs and commercials. Inasmuch as a television tape recording cannot be differentiated from a live program, the use of tape permits the program to be recorded at a more convenient hour for the personnel involved, while still maintaining the live look when it is later broadcast.

Tape itself is responsible for a second revolution in network television. Prior to 1956, the big network shows were usually seen on the West Coast a week or so after they had been broadcast live, in the East. Kinescope recordings (motion pictures photographed from the screen of a station monitor), were used to provide these programs for the West, because the actors and crew were

already busy on another program in the East. Unfortunately, the pictures produced from these recordings were somewhat blurred, and lacking in detail. Today, with tape replacing the kinescope recording, the entire country receives pictures that are equal in quality to the original program. Moreover, using the immediate playback feature of the machine, network programs are now seen the same night, and at the same hour, in each time zone.

Fundamentally, a television tape recording is an electronic brother to the sound movie. Pictures (and sound) are recorded magnetically on a strip of

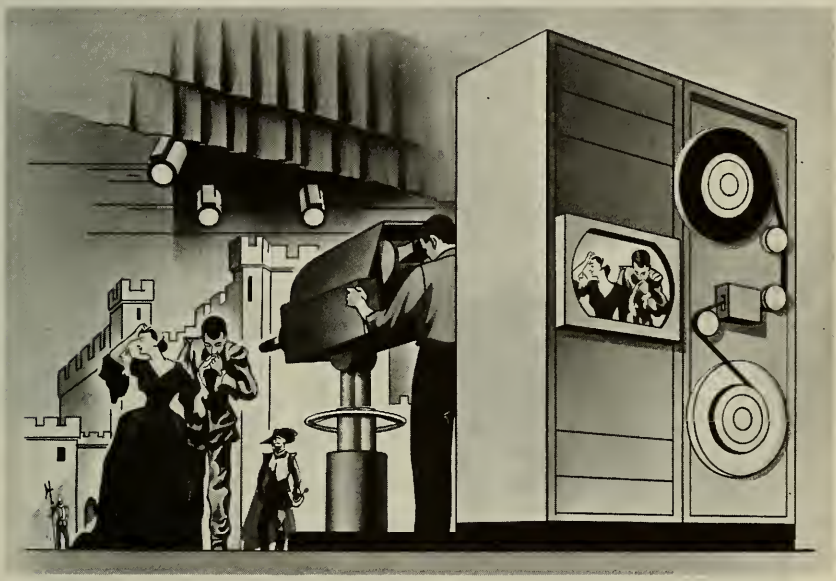
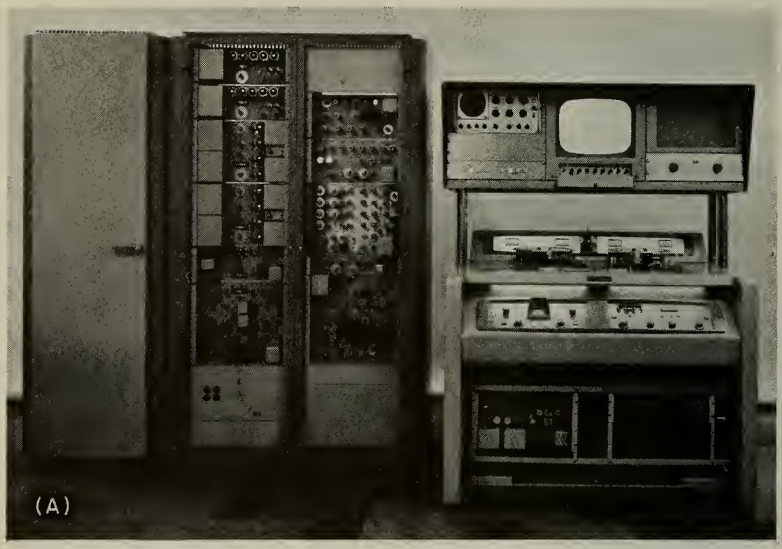


Fig. 1-2. Studio use of video recording as seen by the artist. Immediate playback makes it possible for the dissatisfied director to order a retake while cast and camera crew are still assembled, instead of recalling them, expensively, next day. *Courtesy RCA.*

tape similar to that used in home tape recorders. The recorder itself works in conjunction with standard equipment available at every TV station. The TV camera, for instance, picks up the picture just as it would for a live broadcast. Electrical images from the camera then go through the control room and on to the recorder where they are converted into the magnetic impulses stored on the tape. During playback, the recorder replaces the studio camera. The machine now translates the magnetically recorded information back into electrical images that are indistinguishable from the original, and delivers them to the control room ready for transmission.



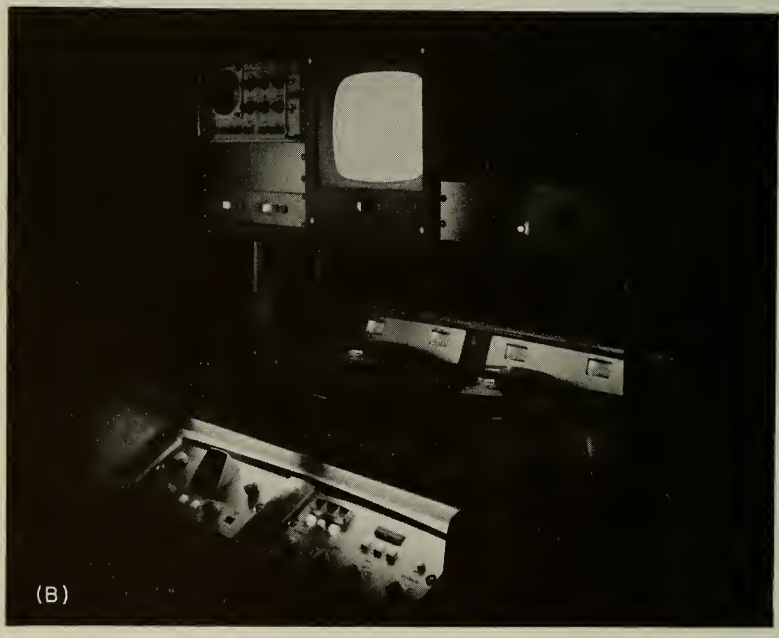


Fig. 1-3. The Ampex VIDEOTAPE television recorder, VR-1000B. The operating position is at the console (B). The two racks with the double door (A) contain all the monochrome circuits not located in the console. The third rack (at far left) contains the color circuitry. *Courtesy Ampex Corp.*

In addition to picture and sound, two other tracks are recorded on the tape, one for cueing and editing purposes, the other for controlling the speed of the machine during playback. Tape used in the machine is 2 inches wide, and 1.4 mils (1.4 thousandths of an inch) thick. To provide strength, the tape is made of Mylar, an exceptionally tough and durable plastic material, one side of

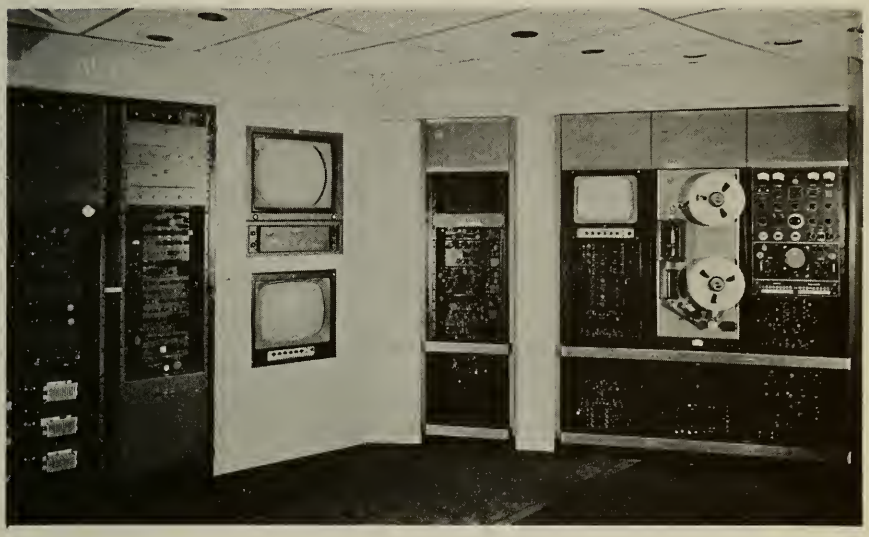


Fig. 1-4. The RCA television tape recorder TRT-1A. The three right-hand racks represent the operating position. A single rack (center) contains the color circuitry, while power supplies and servo electronics are located in the two auxiliary racks. Monitors are for color (top) and monochrome. *Courtesy RCA.*

which is coated with an extremely fine grain uniform emulsion. Standard tape reels hold up to 4800 feet of tape, providing 64 minutes of playing time at the standard tape speed of 15 inches per second.

Audio tape is capable of thousands of replays in a tape recorder. This is not true of a video recording. Currently, the tape is limited to roughly 200 passes through the machine, regardless of whether it is being recorded or played back. After this number of runs the tape starts to deteriorate rapidly. Of course, some tapes can be used more than 200 times, others less. With time, as both tape and machines improve, this average should increase substantially.

Television recorders are made chiefly by two companies, Ampex Corporation and the Radio Corporation of America (RCA). The machines are basically similar, but differ from one another in constructional details and electronic circuitry. The Ampex machine (Fig. 1-3) is built into 2 racks and a console, while the RCA machine (Fig. 1-4) fits into 5 racks. For recording and playing

back color, each machine requires an additional rack of equipment. Subsequent chapters will provide complete descriptions of both machines.

A Brief History of Recording

Although video recording is a very recent addition to the arts and sciences, it has roots that extend far back into the past. Just how far back these roots go we will never know, for it has long been man's dream to leave a permanent record of his accomplishments and day to day activities for his descendants to examine and wonder over. Even our remotest ancestor, the early caveman, left records by drawing crude outline pictures on his cave wall, or by father passing on to his son, details of important happenings. This was the earliest form of recording and it existed for countless hundreds of years. Eventually, it was superseded by writing, printing, photography, the phonograph, and more recently, motion pictures and television tape.

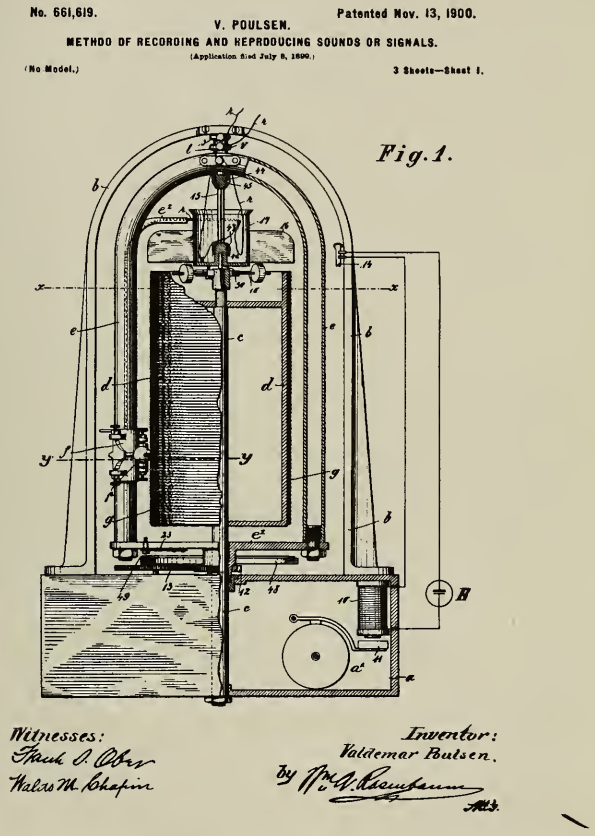
There is much to be learned from early attempts at preserving events or stories for future reference. Most important, is the continuing effort to provide more *realism* in the finished product. Outline drawings, such as those executed by our caveman ancestors, lacked *detail*, a collection of small, unimportant items that go far towards making a picture appear more natural. They lacked, also, *authenticity*, that certain "I was there" feeling that a modern photograph provides, and finally, there was no *animation* (the illusion of motion) in the drawings.

Written and spoken words represent a vast improvement over outline drawings, for with words it is possible to describe the minutest detail and convey a sense of animation. Still, words require a vivid imagination on the part of the reader (or listener) to recreate in his mind the actual appearance of the event being described. For instance, in reading history we must conjure up mental pictures of what a battle was like during the Revolutionary War. On the other hand, *our* descendants will have, among other things, exact detailed descriptions of the various battles of World War II preserved for them on motion picture film. Sound movies leave little to the imagination, for every detail is faithfully copied down, providing the authenticity frequently missing in verbal accounts. Today, with television penetrating electronically into every corner of our world, as well as outer space, tape seems destined to replace the movie in recording the future history of mankind.

The modern art of recording both sight and sound originated with Thomas Edison, although there were many others who also investigated possibilities in this field. In 1877, Edison produced the first practical sound recording. This device took the form of a cylinder on which sound was recorded by indenting the surface in accordance with the pressure of a sound wave. In 1888 he invented the first motion-picture projector, which used a sequence of still pictures projected rapidly one after another onto a screen, the method still in use today. In 1913, by synchronizing his phonograph and motion-picture machines, Edison

demonstrated the world's first sound motion picture. It was not until 1927, however, when electronic amplifiers were available, and accurate, foolproof synchronization between sound and picture had been achieved, that sound movies became practical.

After Edison's phonograph appeared, many inventors sought other methods


No. 661,619. Patented Nov. 13, 1900.

V. POULSEN.

METHOD OF RECORDING AND REPRODUCING SOUNDS OR SIGNALS.

(Application filed July 8, 1899.)

(No Model.) 3 Sheets—Sheet 1.

Fig. 1.

Witnesses:
Frank P. Allen
Walter M. Chapin

Inventor:
Valdemar Poulsen.
By Wm. G. Rasmussen
Atty.

Fig. 1-5. Facsimile of Poulsen's original patent for a magnetic recorder.

whereby sound might be recorded more accurately. Vladimir Poulsen, a Danish engineer, conceived the idea of recording sound by varying the magnetization along a steel wire, for which he received a United States Patent in 1900. Poulsen's machine (Fig. 1-5) used a steel wire over which was passed an electromagnet, the "recording head" of the machine. After making a recording, the microphone was switched out and an earphone substituted. The electromagnet now acted as a pickup device to convert the magnetic pattern on the

wire back into electrical impulses that would actuate the earphone, thereby reproducing the original sound.

Several years later, Poulsen redesigned his machine and produced what was essentially the present day tape recorder in simplified form. Thin wire was stored on a reel and drawn across a stationary electromagnet. After recording, the wire could be rewound and played back. The machine also contained an *erasing* device for removing unwanted recordings. The "Telegraphone" (as he named the instrument) was an advanced idea for its day, but it could not compete with the acoustic phonograph since it contained no amplifiers, and therefore produced a very low sound output during playback. Mostly, the Telegraphone was used as a dictating machine, and some of them, although more than 50 years old, are still in use today.

Magnetic recording languished for some 30 years after Poulsen's invention. Many improvements were made on the basic machine during this interval, but magnetic recording still did not come into widespread use until, in the middle 1930's, several German firms brought out magnetic recorders. These newer models featured electronic amplifiers, and much later, coated plastic tape to replace the steel wire originally used by Poulsen. In the late 1930's similar machines, known as wire recorders, appeared on the market in the United States. To enthusiasts, it was apparent that these machines were capable of much more faithful reproduction than the phonograph records then in use, but the machines still found application mostly as dictating devices. World War II stimulated research into magnetic recording for military applications, with the result that at war's end, the tape recorder had been improved to more or less its present form. After the war, too, prices for magnetic recorders came more into line with what people were willing to spend for the simplicity and fidelity the machines offered.

With the end of the war, television started its cross country march, bringing with it the need for some method of recording both picture and sound. Even in those early days it was apparent that the kinescope recording left much to be desired, and so a search was instituted for better methods of recording video information. Tape seemed a logical choice, for it offered long playing time, an advantage not to be overlooked, as well as high quality reproduction. Accordingly, several tape machines were developed and successfully demonstrated, but these early machines all operated at high speeds and required excessive amounts of tape. Finally, in 1956, a practical machine, operating at the same speed as standard audio recorders, was developed. This became the prototype of the video recorder now in use throughout the country.

Chapter 2

WAVEFORMS AND SIGNALS

Sound and Sine Waves

Recording on disc, film, or tape, involves the storage of information that is undergoing continuous and rapid changes. In order to fully understand the operations of a recording system, it is essential that we first know and understand the types of changes with which the system will work. Sound waves offer a convenient and simple starting point for analyzing these changes.

For our purposes, sound may be defined as a small but rapid variation in air pressure to which the human ear is sensitive. Thus, any device that vibrates, the string on a violin or piano, the diaphragm of a loudspeaker, or perhaps a column of air passing through a wind instrument, all produce sound, since the air surrounding the device will be alternately compressed and expanded by the vibrations. This *compression* and *rarefaction* (or expansion) causes the air pressure to change from its normal value to a slightly different value, increasing for compressions and decreasing for rarefactions.

Figure 2-1 illustrates the creation of a simple sound wave from a vibrating string. At position *A* in the figure, the string is at rest, and any air particles surrounding it are equally spaced from each other. Air pressure is the same at both sides of the string, and is considered normal pressure. If the string is plucked so that it vibrates, let us assume that it first moves towards position *B*, the limit of its motion to the right. As the string moves towards *B*, air particles to the right are pressed closer to each other. This is a compression. The closer the string gets to *B*, the more the particles are forced closer to each other. In this manner the compression builds up in strength until, when the string arrives at *B*, it reaches a maximum.

While the compression builds up to the right, air particles at the left are being spread apart by removal of the string, causing a rarefaction to appear on this

side. The rarefaction also becomes a maximum when the string reaches point *B*.

Since the string is vibrating back and forth, it reverses itself after reaching *B*, and heads for point *C*, passing through *A* in doing so. Air pressure that had been built up on the right, now decreases until, at *A*, it is again normal. Simultaneously, the lowered pressure to the left starts to increase until it, too, reaches normal. The string does not stop at *A*, however, but continues on to *C*, causing the pressure to increase at the left, and to decrease at the right. Both changes reach maximum when the string arrives at *C*. Here the string once more reverses itself and moves back towards *B*, reducing the compression and rarefaction to normal in passing through *A*, and building them up again in the original direction as it approaches *B*. As long as the string continues to vibrate in this manner, compressions and rarefactions will appear alternately on each side of the string. Due to the alternation of compression and rarefaction on one side of the string, the change in pressure is forced to move out, away from the vicinity of the source, as the string continues to vibrate.

Suppose we now consider the cumulative effect taking place to the right of the string. First, a compression is generated, and it starts to move away. The pressure then returns to normal for a moment, as the string goes through *A*, but a

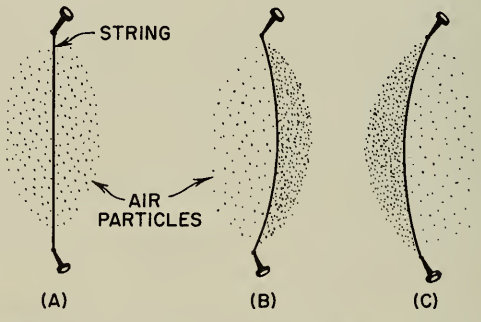


Fig. 2-1. Production of a sound wave from a string.

rarefaction immediately appears. This, too, moves out, and a second compression starts to build up, joining the procession of pressure changes moving away from the string. The second compression is followed by a second rarefaction, still another compression, a third rarefaction, and so on, all moving away in sequence, rarefaction following compression, until the string stops vibrating. This chain of alternations in pressure is a sound wave.

Sound waves are difficult to visualize, but by analogy, it becomes somewhat easier. Almost everyone has seen the effect of dropping a stone into a pool of water. At the instant the stone hits the surface it creates a disturbance roughly similar to that set up by the vibrating string. The disturbance causes water waves to appear by increasing the pressure at the point where the stone first hits the water. As the stone sinks through the water the pressure above it is

reduced. Thus, a compression and rarefaction are generated by the stone, and they move out in ever-widening circles away from the stone, just as a sound wave travels away from its source.

Water waves produced by dropping stones are not quite the same as sound waves, but by another analogy we can show a striking similarity between the two. Consider what we might see if we had a water level view of the waves created by a dropping stone. Figure 2-2 illustrates the effect. Just prior to the time the stone hits the surface, the water level is constant, and is indicated by the straight line to the left of the diagram. As the stone hits the surface, the

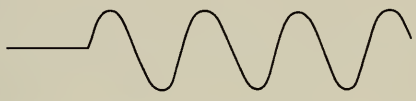


Fig. 2-2. Water waves created by dropping a stone.

waves are generated and pass before our eyes. For the sake of discussion, assume that the compression is generated first. This causes the water level to rise, creating a crest. Note, though, that the water level gradually rises until it reaches the crest, then starts to drop down towards the original water level, passing through this value and continuing on down until it hits a trough (low point) as far below the original water level as the crest was above it. After reaching the trough the water level once more increases, and the action repeats itself.

Figure 2-2 is what might be called a panoramic picture of the water waves, and as such has little significance. On the other hand, if the variations in level passing a fixed point are observed, a new factor emerges, for with dynamic systems (moving water is such a system) variations occur over a given *time* period. This is common to all moving systems, including sound waves. Think again of the vibrating string. Clearly it takes time for the string to move from *A* to *B* and back again. The reverse motion of the string therefore occurs at a later time than that from *A* to *B*.

Looking at Fig. 2-3, it appears to be substantially similar to the diagram of Fig. 2-2. There is, however, a difference, for in Fig. 2-3 increases in time are measured in the horizontal direction, as indicated by the arrow. Zero time appears at the intersection of the axes, and all time measurements commence here. A convenient way to think of this point is to picture an imaginary stop watch that starts to clock events at that instant. As each fraction of a second is ticked off, the diagram indicates the state of the variations taking place.

Figure 2-3 may be used to show variations in sound pressure with time. As a compression builds up, pressure gradually increases until it reaches a maximum value. Similarly, a rarefaction is associated with decreases in pressure. Note that in the illustration a line appears through the middle of the wave. This is called the *zero axis* of the wave, and represents the normal value of pressure,

the value that would exist if the wave were not present. Pressure is measured along the vertical axis. Compressions, since they indicate a rise in pressure, are shown above the zero axis, while rarefactions appear below. The diagram then shows just how the pressure is changed in the wave as time increases. The wave in Fig. 2-3 is called a *sine* wave because the variations are an exact replica of a graph of this trigonometric quantity.

If a compression indicates more than normal pressure, it seems reasonable to say that pressure has been added to that which previously existed. In a like

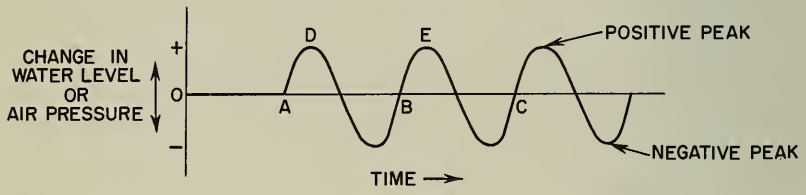


Fig. 2-3. A simple sine wave.

manner, if a rarefaction represents less than normal pressure, some of the original pressure has been removed, or subtracted. Addition of course, is represented by a plus sign, subtraction by a minus sign. For convenience, values above the zero axis are considered positive, or plus, while values below it become negative, or minus. The zero axis itself, therefore, is the dividing line between the positive and negative values. The largest value that the wave reaches in the positive direction is called the *positive peak*, and logically, the maximum negative value achieved by the wave becomes the *negative peak*.

In a sine wave, that portion of the wave that starts at zero on the vertical axis, then proceeds in the positive direction to a peak, diminishes to zero again, continues on to a negative peak and once more returns to zero, is called one *cycle* of the wave. In Fig. 2-3, a cycle exists from *A* to *B*. Another cycle exists from *B* to *C*, followed by a third cycle. If the wave continued on indefinitely, there would be a vast number of cycles, each following the other at a slightly later time. Note, though, that each cycle is an exact duplicate of the others, except for the time at which it appears. As a convenience, we usually consider a cycle as having started from the zero axis, but this is not a necessary condition. A cycle may be measured between any two identical points on the waveform. The portion of the wave from *D* to *E* is just as much one cycle as that from *A* to *B*, the difference being that measurement is started at a different point on the wave.

It is apparent that in the sine wave, any one cycle occupies the same amount of time as any other cycle. In fact, this is one of the defining characteristics of the wave. Suppose now that each cycle in Fig. 2-3 exists for 1/60th of a second. Clearly, 60 such cycles would require one full second, and the *frequency* of the wave (the number of cycles appearing in one second) would be 60 cycles per

second, or 60 cps. Quite often the frequency is referred to as 60 cycles, but it must be understood that the words "per second" have merely been omitted. High frequencies are generally expressed in terms of kilocycles (kc) or megacycles (mc), the former indicating thousands of cycles per second, and the latter, millions. Thus, 15,000 cps is written as 15 kc, while 10,000,000 cps appears as 10 mc.

The *period* of a wave is the time occupied by one cycle, and is the reciprocal of the frequency. Periods are measured in seconds, although for higher frequency waves, the microsecond (1/1,000,000 of a second) is often used. To illustrate, a 60 cps wave has a period of 1/60 of a second.

Sine waves, as we have seen, continuously vary with time. Changes in the vertical direction in the wave are known as changes in *amplitude*, this being another word for size. However, these changes in amplitude make it difficult to discuss the wave, for if one says that the amplitude of the wave is 100 volts, he must also indicate at what time during the cycle this value is reached. To prevent confusion, four values of amplitude are used in discussing and measuring sine waves. These are illustrated in Fig. 2-4. The *peak amplitude* of the wave is the maximum height the wave achieves regardless of where it may occur during the cycle, and is measured from the zero axis to the crest in either the positive or negative direction, but not both simultaneously. The *peak-to-peak* amplitude is the difference between the two peaks, negative and positive, re-

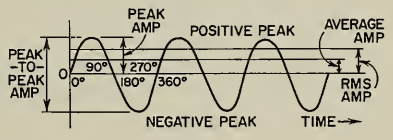


Fig. 2-4. Amplitude and angular measurements in a sine wave.

gardless of where they occur along the time axis. For sine waves, neither of these values is too useful, for the wave reaches them only for a brief instant of time. A more useful measurement is called the *effective* or *rms* (root mean square) amplitude of the wave. This is the most often used sine-wave amplitude measurement. It is equal to 0.707 times the peak amplitude. Finally, there is the *average* value of the wave, 0.636 times the peak. In electronics, this value is rarely used.

Sound waves impinging on a microphone create an electrical equivalent of the sound wave. Thus, a sinusoidal sound pressure wave produces a sinusoidal voltage at the microphone. In the circuits following, this sine wave causes the electrons in the wires to move first in one direction (when the wave is positive) and then in the other (when the wave is negative). This back and forth move-

ment of the electrons constitutes an alternating current. A direct current, on the other hand, consists of electrons always moving in the same direction through the wires, never reversing themselves. Direct currents, or voltages, may be shown graphically, as in Fig. 2-5, but the graph is merely a straight line, having no variation whatsoever. A negative direct current would be represented by a

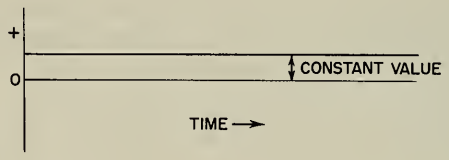


Fig. 2-5. Graphical representation of direct current.

line beneath the zero axis, also unvarying. When voltage varies in amplitude but not in direction (never crossing the zero axis) it is called a *pulsating direct* voltage. Such a voltage is illustrated in Fig. 2-6. If at any time a pulsating voltage crosses the axis, it becomes an alternating voltage. Pulsating voltages are often found in electronic circuits, but not always by choice. Rather, it is the nature of the circuit to produce this type of voltage. In most instances, subsequent circuits break the pulsations down into two parts, one of which, known as the *a-c component*, contains all the variations centered on a zero axis. The

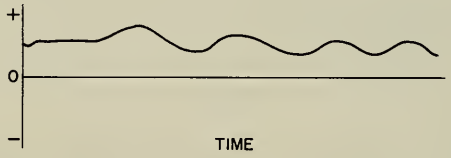


Fig. 2-6. Pulsating d-c waveform.

remaining portion is unvarying, and is known as the *d-c component* of the wave.

Alternating current supplied by the local power companies follows the same sinusoidal variations as shown in Fig. 2-4. Since the generators used to produce the current are rotating devices, it has become standard practice to refer to one cycle of a sine wave in terms of the number of degrees in a circle. One full cycle of a sine wave therefore occupies 360° of rotation. This being the case, a half cycle must correspond to 180°, and a quarter cycle to 90°. In using this terminology, it is customary to start with 0° at the same point used for zero time, the intersection of the two axes. In this manner, then, the positive peak of a sine wave occurs at 90°, it drops back to zero at 180°, goes to a negative peak at 270° and returns to zero at 360°. The positive half cycle of the wave is

that which exists between 0° and 180° while the negative half cycle appears from 180° to 360°.

When two sine waves exist simultaneously in a single circuit, some method of differentiating one from the other is needed. If the two waves are at different frequencies, there is no problem, but if the two happen to be at the same frequency, another relationship appears. Consider the two waves of Fig. 2-7, part (A). Both are sine waves, both have the same amplitude, and what is more, both are at the same frequency. There is, however, a horizontal displacement between the two, and, at any given time, the angular notation for the two is

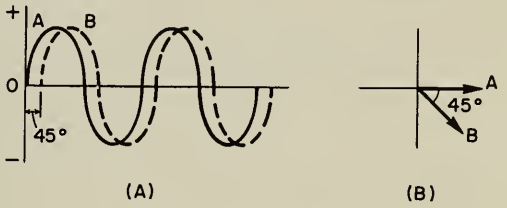


Fig. 2-7. (A) Two sine waves 45° out of phase. (B) Phasor diagram for the two sine waves.

different. This difference remains constant as time increases, inasmuch as each cycle of each wave occupies the same time period. Displacements of this type are known as *phase* differences between the two waves, and are measured in degrees. Generally, the measurement is made between the points where the waves first cross the zero axis, *going in the same direction.* In the diagram, wave *A* crosses the axis at the start (zero time) and rises towards its positive peak. Wave *B* crosses the axis when wave *A* has already gone through 45° of its first cycle. The phase difference is therefore 45°, and wave *A* is said to be *leading* wave *B* by this amount, seeing that it crossed the axis first. If wave *B* is used as a reference, the phase difference is still the same, but in this instance wave *A* is considered to be lagging wave *B* by 45°. Two waves can lead or lag each other only up to 180°, for beyond this point it becomes easier to consider the conditions existing with respect to 360°. For example, if one wave leads another by 270°, it is preferable to state that the first wave lags the second by 90°.

Rather than draw out two waves completely in order to illustrate phase differences, it has become customary to use a phasor diagram, such as that illustrated in Fig. 2-7, part (B). Each line with an arrow is called a phasor, and it represents one of the waves under discussion. The length of the phasor is proportional to the peak amplitude of the wave it represents. A reference angle of zero degrees is considered to exist horizontally to the right, so the relative phase angle of each wave may be measured with respect to this point. In the diagram, wave *A* is at the reference line, while wave *B* is 45° below, or behind, wave *A*. The diagram

therefore illustrates the same conditions as the two sine waves of Fig. 2-7, part (A). It should be noted in passing, that even if wave *A* had not been at the reference line, the difference between the two waves could still be 45°. For instance, if each line had been rotated clockwise by 90°, the difference between them would not change.

Complex Waves

Sine waves are not the only types of waves produced by sound sources. In fact, it is much more common for a sound source to produce a waveform vastly

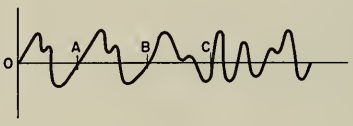


Fig. 2-8. Typical complex waveform.

different from the simple sine wave. Speech and music, for instance, provide waveforms similar to that shown in Fig. 2-8. This is called a complex wave because the pattern of variations is not constant, cycle after cycle. When the change in pattern occurs very rapidly, distinguishing one cycle from another is quite difficult, and so our terms must be redefined.

For complex waves in which no repetitive pattern exists, a cycle may be defined as the variations existing between two points at which the wave crosses the axis going in the same direction. In Fig. 2-8, then, a cycle appears between points *A* and *B* and another, different cycle, appears from *B* to *C*. Due to the lack of symmetry in such a wave, half cycles are nonexistent. Also, with this type of wave, frequency is meaningless, for each cycle requires a different amount of time. There is no time factor common to all cycles, consequently, frequency must be specified for each cycle independently. This is done by assuming that the frequency is that which would be present if all the cycles were identical to the one under consideration. The amplitude of a nonrepetitive complex wave is best measured at the peak of each cycle, and represents the value attained during that cycle only. The rms value varies with the shape of the wave, and is not constant. For complex waves, the rms amplitude may be anywhere from 1% to 95% of the peak value.

Clearly, complex waves may take on many forms. A few, illustrated in Figs. 2-9 and 2-10, are very useful in television and control systems, since they are repetitive, like the sine wave, and may be generated electronically. These waves are named after the physical figure they most closely resemble. Suppose we examine each of them individually.

A square wave is shown in Fig. 2-9. Note that in part (A), each cycle is composed of a positive portion and a negative portion, exactly equal in time. If the zero axis passes through the center of the wave, the two peak amplitudes, positive and negative, are also equal. In the event the zero axis does not pass through the center between the peaks, the wave is said to have a d-c component added to it. The amount of the d-c component is the difference between the zero axis and the actual center line, and it may be either positive or negative, as indicated in parts (B) and (C). For square waves, the most often used measure-

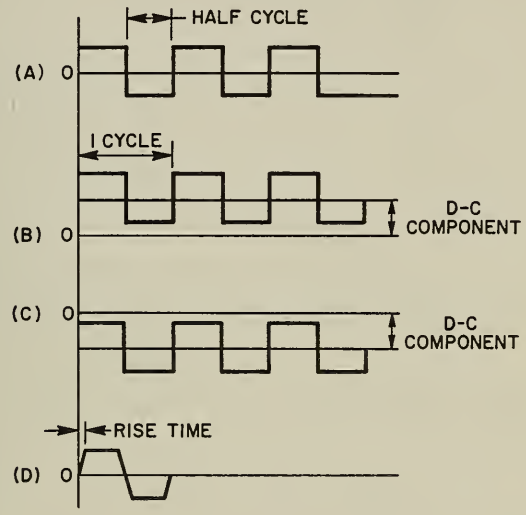


Fig. 2-9. (A) Square wave. (B) Square wave with added positive d-c component. (C) Square wave with added negative d-c component. (D) Rise time illustration.

ment is the peak voltage, although on occasion the peak-to-peak amplitude may be specified.

In observing the square wave, we note that it rises from zero to its peak value almost instantaneously. In practice, such a waveform is exceedingly difficult to generate, particularly in regard to the instantaneous rise. In most cases, practical square waves look more like that shown in part (D), in which the increase from zero to peak takes some small amount of time. The shorter this *rise time*, as it is called, the closer the wave approaches the true square wave. Rise time of a wave is affected by the circuits through which it passes, and extra circuits are often added to equipment to shorten the rise time for some specific application.

The rectangular wave shown in Fig. 2-10, part (A), is similar to the square wave, but it has unequal positive- and negative-going segments. Consequently, it is not possible to call either segment a half cycle. The ratio of the positive

portion of the wave to the negative portion is called the *mark-space* ratio of the wave. If this ratio is known, together with the frequency, the time of each segment is easily calculated. Owing to the lack of symmetry in a rectangular wave, angular notation is not often used except when comparing two waves. If a rectangular wave is reversed, or turned upside down, it is said to be inverted

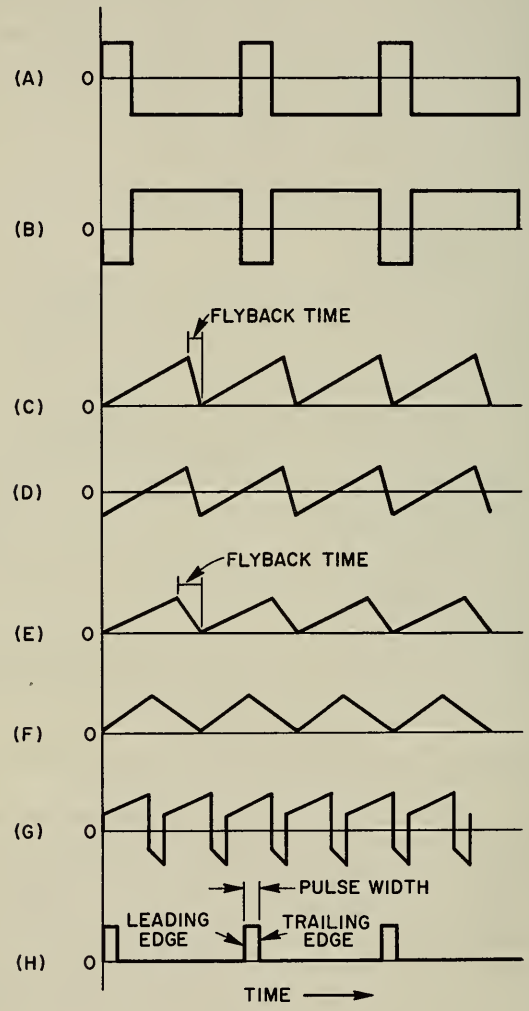


Fig. 2-10. (A) Rectangular wave. (B) Waveform af A, inverted. (C) Positive-going sawtooth waveform with fast flyback. (D) Zero average sawtaoth waveform with fast flyback. (E) Sawtooth with slow flyback. (F) Back-ta-back sawtaath. (G) Trapezoid waveform. (H) Pulses.

rather than shifted by 180° [Fig. 2-10, part (B)]. As with a square wave, rise time is seldom zero.

Another useful waveform is the sawtooth of Fig. 2-10 (C). For this wave, amplitude is usually measured from peak to peak. The zero axis may be at the base of the wave, as shown in Fig. 2-10, part (C). It may go through the center of the wave, as in part (D) of the figure, or it may appear anywhere. When the axis is through the center, the wave becomes symmetrical, as it will then have equal positive and negative values. Several varieties of sawtooth waves exist. Those at (C) and (D) in Fig. 2-10 are said to have *fast flyback*, indicating a rapid drop from peak to base. Conversely, the wave at (E) has a slow flyback. Waveform (F) also has a slow flyback, but it is equal to the rise time, causing the wave to be known as a triangular wave, or more commonly, a back-to-back sawtooth. Adding a sawtooth to a rectangular wave creates the wave at (G), known as a trapezoid.

Waveform (H) in Fig. 2-10 is called a *pulse*. Pulses generally have very fast rises, flat tops, and fast decay. Each pulse exists for a very short period of time. After it disappears, another pulse may come along at some later time. If the pulses are repeated at a constant rate they may be considered as a rectangular wave with a d-c component. Pulses are described in terms of *pulse width*, the time (in microseconds) during which the pulse exists. The front of a pulse, or better, that part closest to zero time, is called the *leading edge*, while the back is known as the *trailing edge*.

When circuits operating with complex waves become defective, the oscilloscope, illustrated in Fig. 2-11, is a useful tool, displaying on its screen the waveform of the circuit being tested. The controls serve to lock the wave in place, and permit viewing anything from a portion of one cycle up to 20 or more cycles of the wave. The oscilloscope also finds application as a peak-to-peak voltmeter for any waveform, and as a frequency, or phase-angle meter.

Block Diagrams

The analysis of complicated electronic circuits is made easier if they are treated as a group of small, interconnected, units, each one having a particular function in the overall arrangement. Instead of drawing out each circuit, a block is substituted, and labeled in accordance with what the circuit is designed to accomplish. A group of blocks with lines between them to indicate the electrical connections, is known as a block diagram. Such a diagram shows at a glance all the interrelated major components of a complete circuit, and permits discussion of the circuit operation without getting bogged down in details. As a convenience in following the operations, operating controls are shown on the block diagram by a small symbol with an arrow through it, located close to the position the control would normally occupy in the circuit. Tube type numbers are often placed within the block to provide additional information. However, if several tubes are of the same type, confusion might result in a written

description of the circuit, so a sequence of numbers such as V1, V2, V3 etc., is used to indicate the stages. In large-scale equipment, where subassemblies are often used, extra digits may be added to the tube code numbers to specify the subassembly involved.

Vacuum tubes require power in order to operate. The power delivered by a-c lines is unsuited to this purpose, for the tubes need dc. A power supply, commonly omitted from block diagrams, converts the power line ac to useful dc

Fig. 2-11. Typical oscilloscope: an invaluable waveform checker. Model shown is the Tektronix *545* wideband oscilloscope. *Courtesy Tektronix, Inc.*

and passes this on to the other circuits. Voltages supplied to the tubes by a power supply are called *operating voltages*, since without them the tubes could not operate. Explanations of circuit operations customarily neglect the values of the operating voltages, unless these are necessary to an understanding of the circuit.

Voltages sent in to an amplifier from a microphone, camera, or other source, are known as *signal voltages*, or signals. This one term is used for both input and output voltages. As a rule, signals are complex waveforms, but in certain control applications they may be dc. In block diagrams, the interconnecting lines indicate signal paths, and the arrows show the direction in which the signal passes from one stage to the next.

Let us now examine Fig. 2-12, the block diagram of an amplifier. At the extreme left is the microphone. A line ties this to the first block and shows the signal path. The first block is designated V1, and a brief description is given by the name of the stage, voltage amplifier. The name itself tells much about the operation of this block. Clearly, it amplifies voltages fed into it, and its

output must then be larger than its input. Voltage amplifiers possess the characteristic of inverting waveforms between input and output. Consequently, if the input is a sine wave, the output is not only larger, it is 180° out of phase with the input.

The output signal of V1 in the diagram is sent to V2. Between the two blocks appears a symbol indicating the volume control. Amplifier V2 is also classed as a voltage amplifier, so everything noted about V1 is also applicable to this stage. From V2, the signal is passed to V3, a phase inverter, or, in some cases, a phase splitter. This, too, is an amplifier, but it provides two outputs, one to each power amplifier. These stages convert the signal voltage they receive into output power suitable for operating a loudspeaker or other load. Power amplifiers require large input signals, and for this reason they are preceded by several stages of voltage amplification. Transformers are normally used to connect the output of a power amplifier to the load.

There are many applications in which voltage amplifiers are useful. Because of this, it is helpful in a block diagram to specify the service for which the circuit is intended. For example, instead of referring to V1 in Fig. 2-12 as just a voltage amplifier, it would be better to call it an "audio-frequency (a-f) voltage amplifier". This immediately informs us that the circuit is designed to handle only audio frequencies, from 20 cps to 20 kc. In radio and television receivers, some voltage amplifiers are called upon to handle much higher fre-

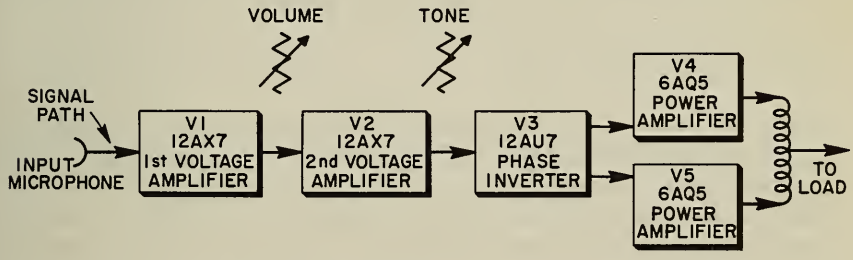


Fig. 2-12. Block diagram of an audio amplifier.

quencies. Accordingly, we find radio-frequency (r-f) amplifiers and intermediate-frequency (i-f) amplifiers in these circuits. R-f amplifiers handle frequencies above 500 kc in radio receivers, and above 50 mc in TV sets. I-f amplifiers operate with frequencies between those of the r-f amplifiers and a-f amplifiers, hence their name. Both r-f and i-f amplifiers utilize inductance and capacitance to tune them to the frequencies in use, and for this reason they cannot amplify audio frequencies. Audio amplifiers, on the other hand, have no such arrangement, and generally do not operate above 50 kc.

Radio and TV receivers contain several other types of circuits that are equally important. One, known as an *oscillator*, has no input signal. Only operating

voltages are applied to this circuit, yet it supplies an output signal, sine waves in radio receivers, and repetitive complex waves in television systems. Another circuit, the *mixer*, has two inputs, but only a single output, either the sum or the difference between the two input frequencies. *Demodulators*, sometimes called detectors, change r-f signals to a-f for use by a loudspeaker. Finally, *rectifiers* are used in the power supplies to convert ac to dc.

Amplifiers and other electronic circuits are connected together by *coupling networks*. These are electrical circuits that permit signal voltages from one stage to pass on to the next, but prevent the operating voltages from doing the same thing. A-f voltage amplifiers are most often coupled together with resistance-capacitance networks, and are therefore called R-C coupled amplifiers, or just R-C amplifiers. R-f and i-f amplifiers may be R-C coupled, but it is more common to find transformer-coupling used between these stages. In certain instances, the coupling network may be omitted, in which case the circuits are said to be *direct-coupled* to each other. Here, of course, signal and operating voltages cannot be separated from one another.

Some circuits respond quite differently to low and high frequencies. Usually, it is the *time constant*, the product of resistance and capacitance in the circuit, that causes this effect. The time constant is a rough measure of how fast (or slow) the circuit responds to its input signal. A short time constant is one in which the product of resistance and capacitance is less than the period of one cycle of the input signal wave. Conversely, a long time constant implies a product greater than the period of the input wave.

Decibels and Volume Units

Electrical quantities, volts, amperes, and watts, are measured by inserting an appropriate meter into the circuit. This is fine for operating voltages and currents, but signal voltages are best measured in units that are completely independent of the circuit itself. Telephone engineers recognized this fact many years ago, and since they were interested only in sound, developed a measuring unit based on human hearing. This was called the *decibel*, abbreviated db. The db is what is known as a compressed unit. To illustrate, the loudest sound that the human ear can hear without feeling pain, is something in the order of 10,000,000,000,000 times more powerful than the softest detectable sound, but the difference between the two is only 130 db.

Unfortunately, meters built to read amplitudes, or *levels*, as they are called in communication systems, were originally calibrated in terms of the rms amplitude of the signal. However, the rms amplitude of a complex wave has no specific relationship to its peak, particularly when the wave represents speech or music. For this reason, some 20 years ago, the networks and the telephone company developed a new meter substantially similar to the older one, but which could be used for the measurement of complex waves. This was accomplished by paying particular attention to the ballistic properties of the meter. Since the

meter was designed to measure what might loosely be called volume, the quantity measured by the meter was termed *a volume unit*, or vu. The meter itself became known as a volume indicator (vi) (Fig. 2-13). The volume unit is almost the same as the decibel, but it differs in application. In broadcast work, signal metering is invariably accomplished with vu meters, and signal levels are specified in volume units. Differences between two levels, however, are measured in decibels, as is the amount of amplification provided by an ampli-

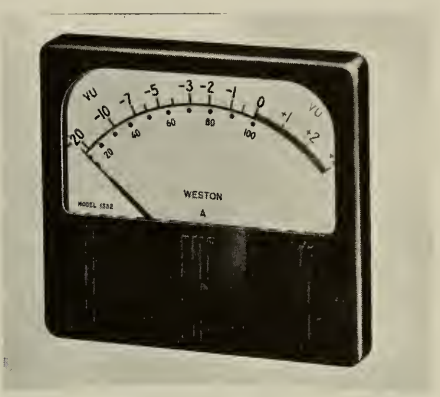


Fig. 2-13. The vu (vi) meter, universally used in broadcasting. *Courtesy Weston Instruments Div., of Daystrom Corp.*

fier. Suppose, for example, that the signal level into an amplifier is −50 vu, and the amplifier increases this by 60 db. The output level is obtained by adding the figures together, providing, in this case, +10 vu. Negative values for volume units do not imply a reversal of direction, they are merely indicative of values of less than 1 milliwatt, or 0.775 volt, these values being known as the zero reference for measurement.

An ever present nuisance in amplifier and communications circuits is noise, a grouping of unwanted signals at random frequencies and amplitudes. Noise is generated by the circuits themselves, and if large enough, may even mask out the desired signal. Invariably, the largest amount of noise in a circuit is produced by the first stage. Here, careful design helps to reduce the noise to a level where it may be ignored. Some noises, however, are due to the nature of the equipment, and cannot be removed. The slight hissing noise in the background of a tape recording, for instance, is caused by the tape. The difference between the actual signal level and the noise level is the *signal-to-noise ratio*, and it is measured in db. For tape recorders, radio receivers, and other equipment used in the home, the ratio is approximately 45-50 db. Professional equipment is perhaps 15-20 db better than this.

Modulation

Transmitting information from point to point is easily accomplished when the two points are connected by wire or cable. When this connection is not available, radio transmission is used, but in order to provide selection between the many signals, each transmitter must operate at a different frequency from all others in the vicinity. This is accomplished by generating a separate high

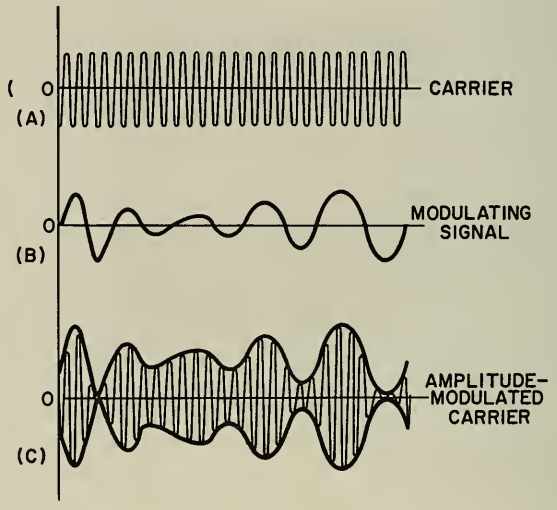


Fig. 2-14. Production of an a-m waveform.

frequency sine wave, known as a *carrier*, in the transmitter, and then adding the information to this wave. The process by which information is added to the carrier is known as *modulation*, and the sum of the carrier and information signal is a modulated wave. The circuit in which the addition is performed is called the modulator. In receiving systems, the modulated wave is picked up by an antenna, amplified, and sent to a demodulator. This circuit subtracts the signal from the carrier, discards the latter, and passes the signal on to other stages.

Figure 2-14 illustrates the production of a modulated wave. The carrier is shown at the top and directly beneath it appears an audio signal, varying in frequency. Modulating (A) by (B) results in waveform (C). The carrier now exists inside the edges of the overall waveform, but its amplitude has been altered in accordance with the changes in the audio amplitude. Wherever the audio signal becomes more positive, the carrier peak-to-peak amplitude increases. For this type of modulation, then, the *amplitude* of the carrier is changed by an

amount proportional to the amplitude of the modulating signal, and for this reason the result is known as an *amplitude modulated* wave, or am. An important consideration in a-m waves is the rate at which the carrier amplitude varies. Note that it is exactly in step with the changes in the audio signal, or in other words, the rate is determined by the frequency of the modulating signal. An a-m wave is said to be 100% modulated when the peak-to-peak amplitude of the carrier rises to twice its unmodulated value for maximum positive modulating signals, and drops to zero for maximum negative modulating signals.

When a signal modulates a sinusoidal carrier, the resulting output frequency is predominantly that of the carrier itself. The original signal frequency disappears completely. However, two additional frequencies are generated within the modulator and accompany the carrier. These frequencies are the sum and difference between the carrier and the modulating signal. Suppose, for example, a carrier is operating at 1000 kc, and it is modulated by a 15-kc audio signal. The modulator output would then be the carrier frequency, 1000 kc, together with 1015 kc, the sum of the carrier and audio frequencies, and 985 kc, the difference between them. These two extraneous values are called the *side frequencies*, and they are very important, for if they are not transmitted along with the carrier, the demodulator in any receiver picking up the wave will produce either no output, or a distorted version of the signal. In practice, it is not necessary to transmit both side frequencies, but this need not concern us here.

The band of frequencies between the carrier and upper, or higher, side frequency is called the upper sideband, while that between carrier and the lower side frequency, is termed the lower sideband. If the audio signal constantly varies in frequency, then the limits of the sidebands will also vary, moving in and out around the carrier. The overall difference in frequency between the upper sideband and the lower sideband is referred to as the *bandwidth* of the signal. For the example cited above, the bandwidth would be 30 kc.

Amplitude modulation presents problems in transmission because a-m receivers are susceptible to atmospheric noises, both natural and man-made. To reduce this interference, systems employing frequency modulation (fm) are often used. Fm differs from am in that the carrier amplitude is not changed. Instead, the carrier frequency, sometimes called the center frequency, is altered, the amount of change being dictated by the amplitude of the modulating signal, as illustrated in Fig. 2-15. The rate at which the carrier frequency changes is dependent upon the modulating frequency. Observe that in the diagram, when the modulating signal is positive, the carrier frequency increases, the amount of increase being directly proportional to the amplitude of the modulating signal. When the modulating signal is negative, the carrier frequency decreases, again in proportion to the decrease in modulating-signal amplitude. Because there is no change in amplitude, it is not possible to define 100% modulation in the same manner as for an a-m wave. Instead, by FCC regulation, 100% modulation for f-m broadcasting corresponds to a 75-kc deviation in either direction from the unmodulated carrier frequency.

As with am, f-m signals also contain side frequencies. For fm, however, there are more than two such frequencies. In fact, a side frequency exists for every integral multiple of the modulation frequency, but only the first few of these are important. Suppose we had an f-m carrier at 10 mc, modulated by a 5-kc signal. The *first* upper side frequency would appear at 10.005 mc. A *second* upper side frequency would be located at twice the modulating frequency above the carrier, or at 10.01 mc, while a third would come in at 10.015 mc, and so on, up to the 75 kc figure specified by the FCC. Additional upper side frequencies

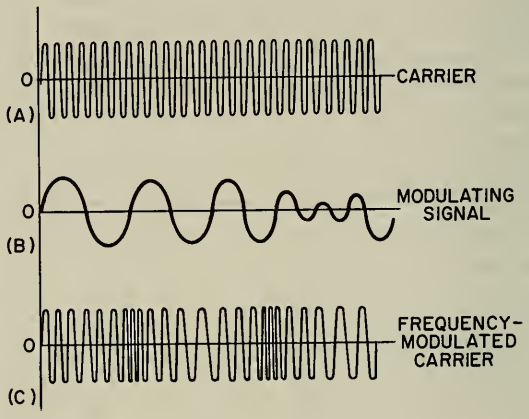


Fig. 2-15. Production of an f-m waveform.

exist beyond this point, but their amplitude is so small that they may be neglected. Lower side frequencies, of course, would also be present, each separated from the other by, in this case, 5 kc, as were the upper side frequencies. The overall bandwidth of an f-m signal cannot be considered in terms such as those used for am, and so the FCC regulations are used. For standard broadcast, then, the bandwidth of an f-m signal is 150 kc. Carrier frequencies are in the vicinity of 100 mc. For standard fm, it is clear that the bandwidth is a *very small* fraction of the carrier frequency.

Vacuum Tubes

Vacuum tubes are the heart of electronic circuits. They are versatile devices that may be used as amplifiers, demodulators, modulators, oscillators, power amplifiers, rectifiers, and in many other applications. Although there are a vast number of different tube types on the market, almost all of them fall into one of four major categories.

The simplest of all vacuum tube types is the diode. Diodes contain two

elements, a cathode used to liberate negatively charged electrons when it is heated, and an anode, or plate, that collects these electrons. The symbol for the diode is shown in Fig. 2-16, part (A). For simplification, the cathode heating arrangement is left out of the symbol. When the cathode is heated, electrons literally "boil off" its cylindrical surface. There is no place for these electrons to go, so they mill around in the space within the tube. A few may reach the plate, but the number is insignificant. If, however, the plate is made positive with respect to the cathode (by addition of a d-c operating voltage), the loose electrons are attracted to the plate by its positive charge, and they swarm towards it, causing a current to flow between the two elements. This current is called the plate current of the tube, and is assumed to travel in the direction of electron motion. Increasing the positive potential at the plate increases the number of

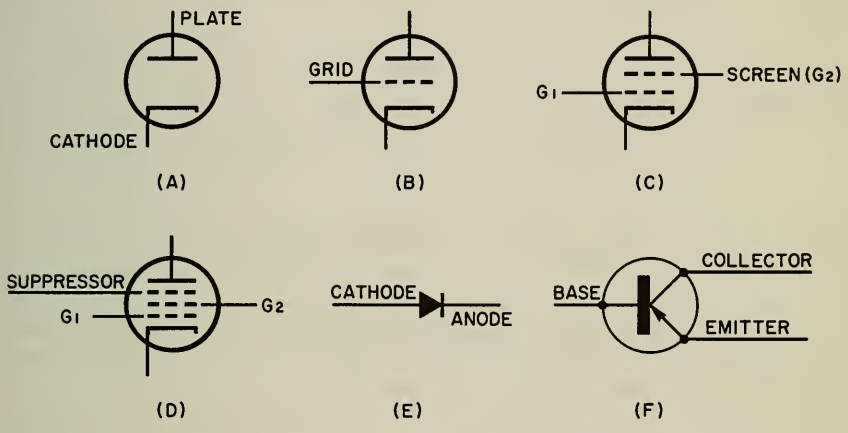


Fig. 2-16. Standard symbols: (A) diode; (B) triode; (C) tetrode; (D) pentode; (E) crystal diode; (F) transistor.

electrons attracted, and thereby increases the plate current. At some point, though, all the liberated electrons will be so attracted, and any further increases in plate voltage can no longer cause the current to increase. The tube is then said to have reached *saturation*, or maximum plate current.

Reversing the operating voltage, so that the plate is negative, has little or no effect in the diode. Since the plate is negative, electrons cannot travel towards it, and no current flows. Even those few electrons that might have reached the plate if it were neutral, are now repelled.

If an alternating voltage is applied to the plate of the diode, current will flow only during the period when the plate is positive, never when it is negative. Thus, the diode may be used to convert alternating current into a fluctuating dc. This type of operation is called rectification, and it is used in power supplies and demodulators.

The diode is converted into a triode by inserting a *grid* between plate and cathode. The grid is a wire mesh arrangement, usually placed closer to the cathode than the plate. Plate and cathode still function as they did in the diode, but the grid exerts an added influence. If the grid is made negative, electrons from the cathode are repelled, and do not reach the plate, even if it is made positive. On the other hand, should the grid be made positive, the electrons would be attracted towards it, but due to its open mesh construction, they pass right on through, and go to the plate. Because the grid is so close to the cathode,

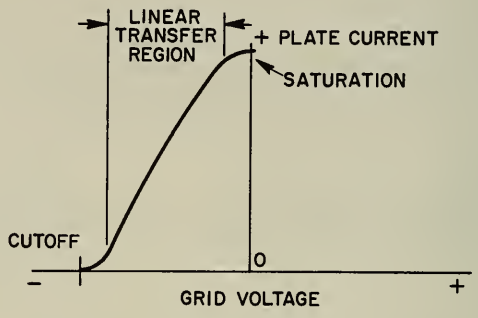


Fig. 2-17. Linear transfer function for a triode.

it has more influence over the plate current than does the plate itself. A very small change in grid voltage is capable of producing a large change in plate current. This is the basis of operation for amplifiers.

In triode circuits, the grid is deliberately made negative with respect to the cathode. The difference in voltage between these two elements is called the *grid bias* of the tube. A small amount of bias does not stop the plate current, for electrons may still go through the open mesh. Increasing the negative potential on the grid does, however, decrease the plate current. Regardless of plate voltage, if the grid is made sufficiently negative to repel all electrons attempting to pass through, there can be no plate current. The grid voltage at which plate current ceases, is the *cutoff* voltage. Plate current can, of course, be increased by making the grid less negative (or more positive), but only up to the saturation point.

Between the limits of cutoff and saturation, a direct relationship exists between grid voltage and plate current. Equal changes in grid voltage produce equal changes in plate current throughout this region. If the relationship between the two quantities is plotted, as in Fig. 2-17, it appears as a straight line, and the tube is said to provide a *linear transfer characteristic.* Nonlinear transfer functions create distortion, and are avoided unless the particular distortion created is useful.

Incoming amplifier signals are applied to the grid of triode amplifiers. The

bias voltage then acts as the zero axis of the signal wave, and the grid voltage varies around this value, creating a like variation in plate current. If the bias is too close to cutoff or saturation, the variations of signal voltage may exceed the limits of the linear transfer portion of the tube curve, causing the output wave to be sliced off at that point. This, too, is distortion, but very often it is desirable. Circuits that slice off sections of an input signal are referred to as clippers, and find application in television and control systems.

Although the triode makes a good amplifier, it has certain limitations. These are overcome to some extent by incorporating a second grid between the first grid and the plate. The result is called a *tetrode.* Signals are still fed into the first grid, now referred to as the "control grid", or grid No. 1. The added grid is known as the "screen grid", or screen, and it is usually operated at voltage either equal to, or slightly less than, the plate. Operating the tetrode with very low screen voltages, cuts off the plate current just as effectively as negative voltages on the control grid.

Adding a third grid, called a *suppressor*, to the tetrode, converts it into a *pentode.* The suppressor, or grid No. 3, is usually tied to the cathode, although this is not essential. Operating the suppressor at highly negative potentials also cuts off the plate current.

In many circuits, solid-state devices are replacing vacuum tubes. These tiny devices, crystal diodes and transistors, offer the same versatility as the vacuum tubes they replace, but in much smaller space and without the need for heating their cathodes. Crystal diodes are exactly what their name implies, two-element devices that will pass current in only one direction. A crystal diode may replace a tube-type diode in any application where the applied voltage and current do not exceed its limitations. Large current applications still require the use of tubes, although the selenium rectifier (a form of solid-state diode) is gradually taking over in this field.

Transistors, of course, represent a completely new approach to amplification. The transistor contains three elements, collector, emitter, and base, corresponding roughly to cathode, grid and plate, in that order. Transistors do not provide voltage amplification, rather, they produce current amplification, and the required operating voltages are very small.

Chapter 3

ELECTRONIC PHOTOGRAPHY

Picture Transmission

Transmitting pictures electronically involves a complicated procedure, due primarily to the difference in the manner in which we hear sounds and view pictures. Sound waves, and their electrical equivalents, form what is known as a *time-sequential* signal. This means that the information they contain is made up of smaller components (called elements or bits) that appear in the wave one after the other. A good example of a time-sequential system is the material you are now reading. Each word follows a preceding word and is in turn followed by another word. Reading these lines, we observe one word at a time. A group of words makes up a thought, but clearly, it takes time to read a sufficient number of words to grasp the thought. Complex waves are time-sequential signals, then, since cycle follows cycle, and half cycle follows half cycle.

Sight, on the other hand, does not involve a time sequence. When the eye focuses on an object, the complete pattern of that object and its surroundings is instantly impressed on the retina of the eye. A large number of nerve paths deliver the pattern to the brain for interpretation. To duplicate this instantaneous action of the eye and brain electronically, would require as many individual signal channels as there are never paths between retina and brain, an obvious impossibility with today's technology. There is, however, a simpler approach. The picture to be transmitted may be broken up into tiny segments, each a *picture element*, and then sent out as a time-sequential signal, element following element. At the receiving end, the elements may be reassembled to create the desired image on a television screen.

In practice, a television signal is two time-sequential signals in one package. In order to produce the illusion of motion, television, like the movies, projects

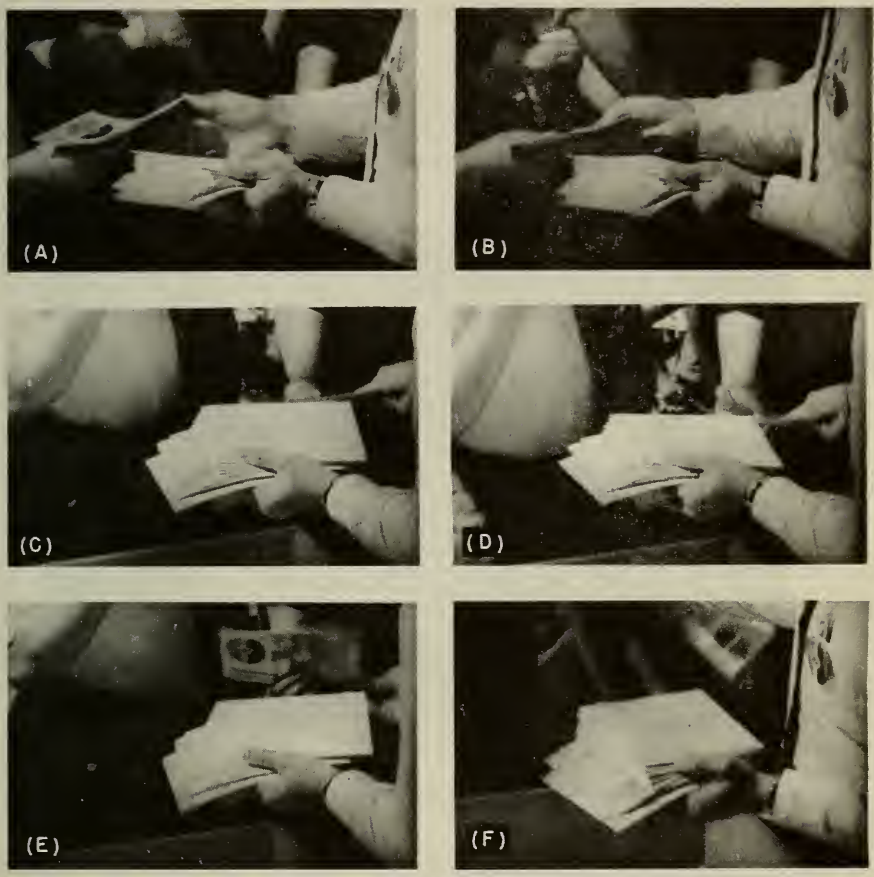


Fig. 3-1. Motion-picture film showing frames with slightly different pictures. *Courtesy NBC.*

a series of still pictures one after the other in rapid succession. Each still picture, or *frame*, is slightly different from the others, as Fig. 3-1 shows. If the rate at which frames are flashed on the screen is high enough, the eye no longer sees them as independent pictures, but blends them together into a continuously moving image. The illusion of motion is created in motion pictures by projecting 24 frames per second on the screen. For reasons to be discussed later, the television system contains 30 frames per second. Each frame transmitted by television is broken down into picture elements that are then transmitted sequentially. Thus, there are 30 groups of picture elements, each group a time-sequential signal itself, transmitted one after the other each second.

Consider now the picture in Fig. 3-2. It contains white, black, and various degrees of gray, all reproduced with a single shade of black ink. To accomplish this feat, the printer first converts the picture into row after row of tiny dots, each a picture element. The dot pattern is then inked, and used to print the picture. Figure 3-3, an enlargement of Fig. 3-2, illustrates the method employed. Where white appears, there are very few dots and so the white surface of the

Fig. 3-2. Photograph illustrating picture elements. *Courtesy NBC.*

page shows through the pattern. For black sections, a huge number of dots are placed close to one another, completely blacking out the page. Gray segments are reproduced by using less dots than for black, but more than for white. Dark gray, being close to black, contains almost as many dots as the black portions, while light gray has just a few more than white. When the dots are made small, as in Fig. 3-2, the eye sees their pattern as a black and white rendition of the picture.

For television, a similar system of picture elements is needed. Since each frame differs from its forerunner, it is not possible to concentrate the elements for black and thin them out for white. Instead, a constant number of elements are arranged in rows and columns, and the brightness of each element is varied. This is the equivalent of printing a picture on black paper with white ink, except that, in this case, gray is produced by reducing the brightness, and black by having no brightness at all.

The television camera, shown in Fig. 3-4, generates the picture elements. This camera is basically similar to other cameras, except that a tube replaces the

film. There are several types of tubes used in TV cameras, the iconoscope, the image orthicon, and the vidicon. The latter two are used extensively, due to their greater light sensitivity. Both operate by creating an electronic image of the picture to be transmitted, while the iconoscope operates in somewhat simpler fashion. For this reason, only the iconoscope will be discussed here.

The iconoscope (Figs. 3-5 and 3-6) consists of an evacuated glass envelope

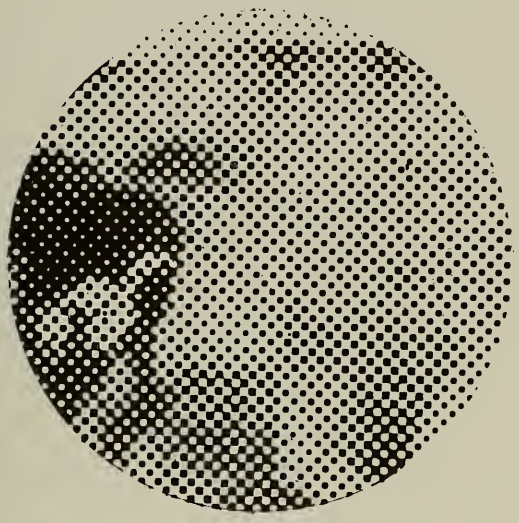


Fig. 3-3. Enlarged version of Fig. 3-2 showing halftone screen. *Courtesy NBC.*

surrounding two major components, a *mosaic* and an *electron gun.* Light rays from the subject being photographed are focused on the mosaic. This is a sheet of insulating material coated on one side with an electrical conductor, and on the other, the side closest to the lens, with a large amount of tiny silver-caesium globules, each insulated from its neighbors. Each globule acts as one plate of a capacitor in conjunction with the conductive coating on the opposite side of the mosaic.

When light strikes a globule, it releases electrons and acquires a positive charge. Bright light generates a higher charge than dim light. Thus, over the surface of the mosaic, the images of bright objects cause high charges to appear on the globules they strike, while black objects produce no charge. Gray components in the picture produce some intermediate amount of charge, the exact amount depending upon the shade of gray. Summing it up, the optical image on the mosaic is changed into a pattern of electrical charges varying in amplitude over the surface of the mosaic, in accordance with the brightness of the scene. The charges, once produced, remain on the mosaic until they are removed

electrically. It is the job of the electron gun to remove them, and in so doing, create the picture signal.

An electron gun consists of a cathode that liberates copious quantities of electrons, together with several other electrodes that form these electrons into a very thin beam directed towards the center of the mosaic. A set of coils

Fig. 3-4. Typical television camera. Courtesy RCA.

wrapped around the neck of the tube deflect the beam so that it travels *horizontally* across the mosaic from side to side and back again, 15,750 times each second. A second set of coils, at right angles to the first set, moves the beam *vertically*, up and down the mosaic, 60 times per second. The combination of vertical and horizontal deflection causes the beam to sweep across the mosaic from the lower left hand corner to the upper right hand corner, in a pattern of horizontal lines. This is called *scanning* the mosaic.

As the beam sweeps across the face of the mosaic it touches in turn each of the globules. Since the globules are positively charged, they lack electrons, and the passing beam supplies whatever electrons are needed to neutralize the globule charge. As soon as this happens, the globules recharge themselves from the optical image focused on the mosaic, and prepare themselves in this way for the next sweep of the beam.

Now, the globules act as capacitors, but it is not possible to discharge a capacitor instantaneously, so at the instant the positive charge on a globule is wiped out by the beam, the back plate acquires a negative charge and a negative voltage appears at its terminal. Black sections of the picture, which involve no globule charge, produce zero output voltage from the back plate, while bright

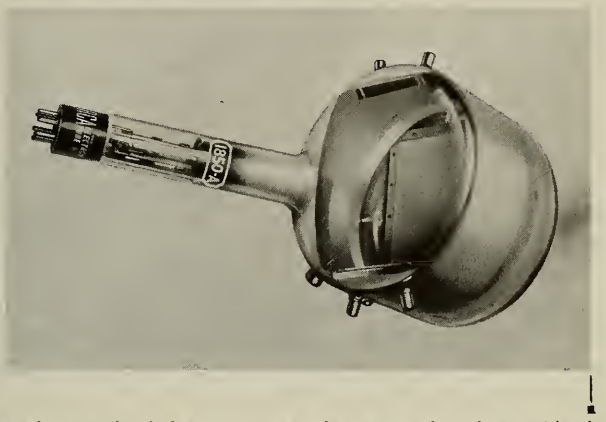


Fig. 3-5. Photograph of the iconoscope. The rectangular plate inside the tube is the mosaic. *Courtesy RCA.*

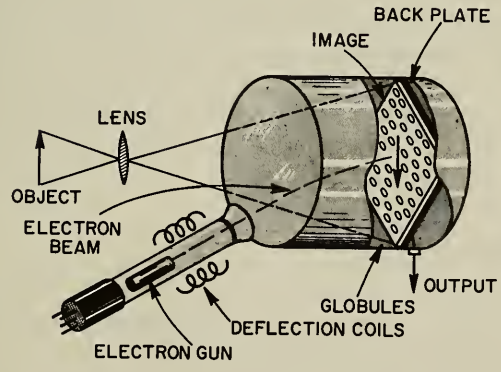


Fig. 3-6. Diagrammatic drawing of the iconoscope. *After RCA.*

segments, with corresponding high globule charges, cause a very high negative output voltage. Actually, the diameter of the beam is larger than that of a globule, and as it passes over the mosaic it discharges a group of globules simultaneously, producing an output proportional to the average illumination on the group. It is the beam diameter that determines the size of the picture elements,

and it is the sweep of the beam that establishes the timing of the output signal.

The varying output from the mosaic constitutes a picture, or video, signal. After amplification, it is sent to the transmitter for broadcasting. At the receiving end, the signal is picked up by an antenna, amplified, demodulated, and sent on to a picture tube, or *kinescope*, to recreate the picture. During transmission, the black component of the signal is transmitted as a maximum voltage, and the white segments as a minimum voltage, for reasons discussed later.

The inside of the faceplate (front) of a kinescope is coated with a phosphorescent material (the phosphor) that gives off white light when it is struck by a beam of high velocity electrons. At the neck of the tube is an electron gun practically identical to that used in the iconoscope. The gun produces a beam of electrons with a diameter equal to the size of one picture element. The received video signal controls the number of electrons in this beam. It is directed down the tube and strikes the screen in the rear. If the beam contains many electrons, the screen is brightly lit at the impact area. Less electrons cause correspondingly lower illumination. With very few electrons, the impact area is quite dark, and if the beam is cut off, there is no illumination. By contrast with the brightly lit portions of the screen such an area appears to be black. The video signal therefore causes the screen to reproduce black, gray, or white, in accordance with the light originally striking the mosaic at the camera.

To recreate the original camera scene on the kinescope, we must arrange for each picture element to appear in its correct place on the screen, for if this is not done, the result will be a completely confused pattern that makes no sense. As with the iconoscope, two sets of coils are used around the neck of the kinescope to deflect the beam horizontally and vertically. If each element is to be properly located, it becomes necessary to synchronize the motion of the beam in the kinescope to that in the camera. Special synchronizing pulses are therefore sent out from the transmitter to keep the receiver deflection circuits in step with the camera circuits. With the two beams thus locked together, each picture element at the kinescope falls into place.

Scanning Patterns

Let us now examine in more detail, the horizontal and vertical motion of the electron beams in both camera and picture tube. Inasmuch as these scanning patterns are identical, we need consider only the kinescope. Remember, however, that in the camera, the pattern will be inverted, since the lens on the camera creates an inverted optical image on the mosaic.

Picture elements in any one frame are arranged along a series of 525 horizontal lines, placed one under the other from the top to the bottom of the picture. The pattern produced by these lines is known as a *scanning raster*, or, more commonly, just raster. The raster is produced on the kinescope by forcing the electron beam to move rapidly from left to right across the screen, while simultaneously moving from top to bottom at a much slower rate. The horizontal

velocity is so great that the beam appears to trace out a line on the screen as it moves across, rather than a series of dots. FCC regulations provide that commercial TV systems operate with 30 frames per second, so if 525 lines appear in each frame, there must be 525 × 30, or 15,750, lines produced in each second. Each line therefore requires 1/15,750 of a second to move across and back. Time wise, this is the equivalent of 63.5 microseconds. During approximately 53 microseconds of this time, the beam moves with constant (or linear) velocity from left to right. In the remaining 10.5 microseconds, it is returned from the right side of the screen to the left, and made ready to start the next line.

We must now digress for a moment. In motion pictures, 24 frames per second are projected. However, each frame is projected twice, to reduce the sensation of flicker that might be perceived by the eye. Now, flicker is more noticeable if the observed picture is very bright and small. Compared to the movies, a TV screen is both smaller and brighter, making any flicker more noticeable. To eliminate the flicker, TV pictures have to be projected at a rate in excess of 48 frames per second. Due to bandwidth limitations this cannot be done, and so some other flicker reduction method must be found. Fortunately, the human eye is easily fooled, so we take advantage of it. Instead of reproducing 525 lines from top to bottom directly, 262½ lines are traced out between top and bottom in 1/60th of a second. Reaching the bottom, the beam is sent back to the top, where it commences to trace out another 262½ lines in the next 1/60th of a second. This second group, however, fits *in between the lines of the first group.* Each group of lines is called a *field*, and two such fields comprise a frame. Note that if 262½ lines are created in 1/60th of a second, it is exactly the same as if 525 lines had been generated in 1/30th of a second. We therefore have an equivalent flicker rate of 60 changes per second rather than 30, but the system still handles 30 frames per second. The process of fitting one field between the lines of another is called *interlaced scanning.*

Suppose a beam of electrons is generated by a gun and sent towards the kinescope screen. In the absence of a deflection system, the beam would strike the screen somewhere near the center. Each electron in the beam is surrounded by a magnetic field. If a fixed magnetic field is now placed so that the beam passes through it on its way to the screen, the interaction of the two fields will create a force that changes the direction of motion of the beam. The stronger the external field, the more force is applied, and the further the beam is deflected from its straight path. Reversing the direction of the external field reverses the deflecting force. For television deflection, the external field is produced by passing a sawtooth current through the deflecting coils on the neck of the kinescope.

Examine the sawtooth of Fig. 3-7. Observe that it has a zero axis through its center, together with a fast flyback. Whenever the wave is at zero, no current goes through the coils, and deflection is nonexistent. When the sawtooth is made negative, as at its lower peak, the external field of the coil causes the beam to shift to one side. Reversing the polarity of the sawtooth reverses the deflection direction. Let us assume that the negative peak causes the beam to be de-

flected to the extreme left of the raster. As the sawtooth becomes less negative, there is less deflecting force, and the beam moves in towards the center, reaching it when the sawtooth crosses the zero axis. Now, as the sawtooth increases in the positive direction, its polarity has been reversed, and the beam is deflected more and more to the right until, at the sawtooth peak, it has reached the right side of the raster. At this time, the sawtooth reverses itself and almost instantly drops back to its negative peak, causing the beam to fly back very rapidly to the left side. The action now repeats itself. Each cycle of the sawtooth causes the

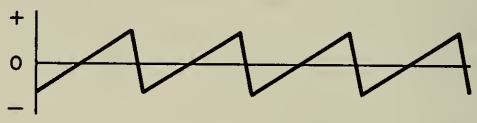


Fig. 3-7. Current sawtooth used for deflection.

beam to sweep across the screen and back only once, then the next cycle takes over. It then becomes clear that if 15,750 horizontal lines are to be swept out in a second, it will take that many cycles to perform the task. The horizontal frequency of the television system is therefore 15,750 cps.

Vertical deflection is accomplished in the same manner, but in this case, the sawtooth frequency is only 60 cps, required to provide two fields per frame. In commercial television, the field frequency and the vertical frequency are identical, 60 cps, but the frame frequency is 30 cps. Both vertical and horizontal sawtooth waves are created in the TV receiver by oscillators.

Figure 3-8 illustrates a typical raster. For convenience, only a few lines are shown. Assume that both the horizontal and vertical sawtooth waves are at their negative peaks. The beam is therefore at the top left of the raster, and as the two waves start to increase in amplitude, the beam moves both across and down. Although the horizontal sweep of the beam on any one line takes only 53 microseconds, the vertical sweep from top to bottom in one field requires about 16,000 microseconds. In 53 microseconds, then, there is very little downward movement, but it is sufficient to make the right side of any line appear slightly lower than the left (in the figure this has been deliberately exaggerated for illustrative purposes). Now, as soon as the beam reaches the right side of the raster, the horizontal sawtooth reverses itself, causing the beam to retrace its path back to the left. This takes only 10.5 microseconds. Due to the higher retrace velocity, the retrace lines (shown dotted) appear somewhat dimmer than the trace lines (shown solid). During the retrace period, of course, the beam is still moving downward, but not as far as during the trace period. In any event, when the beam reaches the left side, it is lower than when it first started out to trace the line across the screen. Since the horizontal oscillator continues to generate the sawtooth, the beam once more starts across and traces out a

second line. At the right edge of the raster the beam is again lower than at the left, and as it reaches the right, retrace again starts, forcing the beam back again to the left. This operation continues all the way to the bottom of the screen, tracing out line after line, one under the other.

As the beam approaches the bottom of the screen, the vertical sawtooth is approaching its positive peak. Actually, the peak is reached halfway through one horizontal line, and vertical retrace begins immediately at this point, as shown in the figure. Because of the comparatively slow motion of the beam in the vertical direction, several horizontal lines occur during the vertical retrace period. These too, are indicated in the figure. On a blank raster, with no video signal, these retrace lines appear as brightly illuminated steeply tilted lines. At the top of the raster, the relative timing of the horizontal and vertical circuits is such that the vertical trace starts halfway through a line. The vertical sawtooth however, is now at the same negative peak as when scanning first started. Thus, we see that the position of the beam at this time is exactly as high on the raster

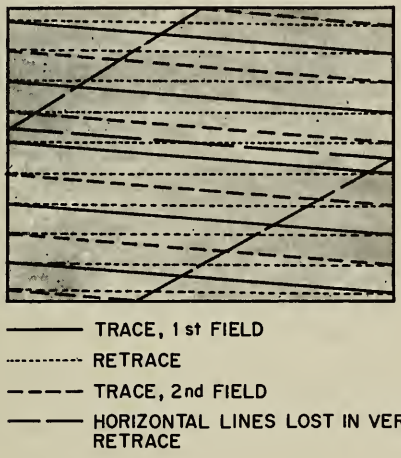


Fig. 3-8. A typical raster.

as the start of the first line from the previous field. Inasmuch as that line had dropped slightly by the time it got halfway across, the half line that now starts is *above* the first line from the other field. At the end of this extra half line, horizontal retrace again takes place, causing the beam to move back to the left. At this time, though, it is higher than the start of the second line from the first field, but lower than the first line of that field. In fact, it is right in the center between the two. All the way down to the bottom of the raster, each line swept out in this second field falls between two lines from the preceding field. At the bottom, the relative timing between vertical and horizontal circuits causes

vertical retrace to start at the end of a horizontal line, and after retrace, the two sawtooth waves are both at their negative peaks, so the entire sequence starts over with the first field being traced out again.

The Video Signal

In the television system, as we have just seen, each field comprises 262½ lines, but a few of these occur during retrace and are not available for use in the picture. Actually, only about 240 *working* lines (or lines used to reproduce the picture) appear in each field, so a frame contains approximately 480 working lines. If we now consider that the picture elements are circular, and the thickness of a horizontal line represents the diameter of the element, there will be 480 elements in column form from top to bottom. Now, camera tube mosaics are fashioned so that the dimensions of the television picture are similar to that of the movies, 4 units wide and 3 units high. This ratio of width to height is called the aspect ratio. In any event, if the width of the picture is 4 units while the height is 3 units, there must be 4/3 as many picture elements along any one line as there are from top to bottom. Thus, there are approximately 640 picture elements per line. The number of elements in a frame is the product of the horizontal and vertical elements, 640 × 480, or just over 300,000 elements in a frame. But, 30 frames are transmitted each second, so there must now be 9,000,000 picture elements transmitted each second, one following the other. The rate of change of brightness on the screen due to these elements is called the *video frequency.*

Think now of what that last figure implies. Imagine a picture made up of alternate black and white elements. In other words, the first element on the first line is black, the second one is white, the next black, and so on across the line. On the second line, the first element is white, and the pattern continues. Clearly, the camera output would alternate between zero and maximum to produce this pattern. What is more, the alternations would appear regularly, and the video signal would resemble a square wave, each element becoming a half cycle. But, it takes 2 half cycles to make a full cycle, so the 9,000,000 elements give rise to a square wave with a frequency of 4.5 mc! Since there can be no faster change in the picture, this represents the highest possible video frequency.

At the other extreme, think of a picture that is either all white or all black. No change whatsoever occurs from element to element, so the video signal is a constant voltage, unvarying, or dc. This, of course, is the lowest possible video frequency. The video bandwidth is the difference between this lowest frequency and the highest, or 4.5 mc. Contrast this with the audio band, a mere 20 kc!

Let us now trace out one line of video information. Assume that a TV camera is focused on the pattern of Fig. 3-9. At the extreme left, the pattern is a medium gray, causing the camera output to be somewhat negative, as shown in part (B) of the figure. The output voltage remains at this level until the wide black bar appears, at which time the video signal goes to zero, remaining

there until the white section is reached. For white, the camera output is highly negative. Continuing on, the next black bar raises the video signal to zero again, from where it once more drops to a negative value for the succeeding gray section. Observe that for light gray, the signal is more negative than for dark gray. The light gray section is followed by a very thin black bar, shown

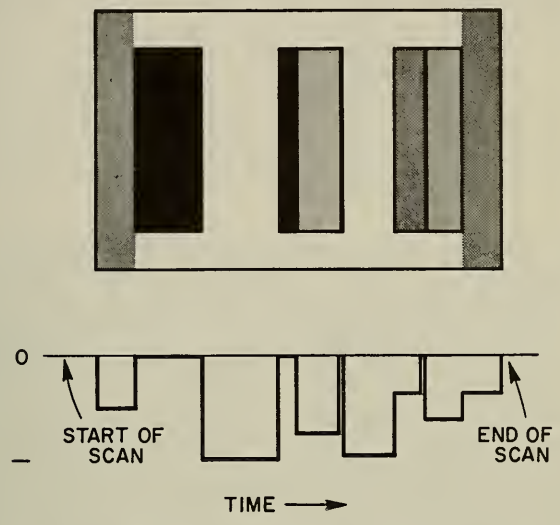


Fig. 3-9. Generation of a video signal from a pattern.

as a spike (or thin pulse) in the video signal. As indicated by the figure, the video signal undergoes additional changes as the line is scanned.

As we have seen, the video signal is a complex wave, with constantly changing amplitude. The exact video frequency, of course, depends upon what part of the scene is being televised, and the rate of change of brightness involved in that portion of the scene. Broad outlines, dim or solid backgrounds, represent no change in illumination for a relatively long period of time along a line, so the resulting video frequency is quite low. Fine detail, on the other hand, causes very rapid amplitude changes in the signal, and this is synonymous with high video frequencies.

Resolution is a term used in photography to roughly indicate picture quality. High resolution means that picture elements are small, and fine detail shows up well. In TV receivers, element size cannot be altered, but, if the high video frequencies are missing, rapid brightness changes from one element to another disappear. For TV, then, resolution is another way of expressing the ability of the system to reproduce detail. Low resolution pictures lack detail. High resolution pictures have it.

Synchronization

The raster of Fig. 3-8 is characterized by visible retrace lines, both horizontally and vertically. Picture elements, however, only appear along the trace lines, and the presence of a visible retrace detracts from the picture. It would seem wise to eliminate these unwanted lines, and this is not difficult. All that is needed

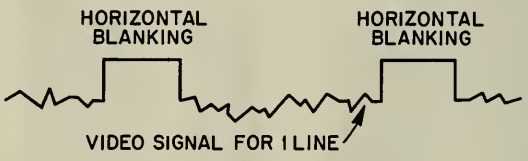


Fig. 3-10. A video signal with horizontal blanking added.

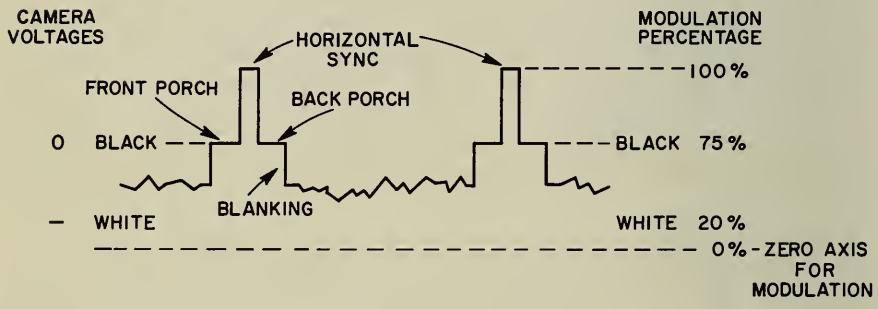


Fig. 3-11. Horizontal sync added to blanking.

is to transmit the equivalent of a black signal between lines and fields. Such a signal would cut off the beam during retrace periods, thereby eliminating the undesired effect. This *blanking* signal, as it is called, has to be generated at the transmitter, and properly timed. For the horizontal circuits, blanking should commence as the beam reaches the right edge of the raster, and it should stop as soon as retrace has been accomplished. As a practical matter, blanking is made somewhat longer than this, so that nonlinearities in the sawtooth current at the start and finish of each line are also removed. This removes distortion at both edges of the picture. Similarly, vertical blanking starts several lines before the bottom of the raster, and continues until the downward sweep of the beam is linear. The effect of the blanking may easily be seen on any receiver by reducing the size of the picture with the vertical size control, until top and bottom are about 2 inches away from the edges of the mask. If the brightness is now advanced, gray lines will appear at both top and bottom, as will the

horizontal lines used during vertical retrace. When the brightness is returned to normal, the blanking signal removes these extraneous lines.

Blanking time between lines or fields is a small percentage of the total time of one line or field. In order to reduce the possibility of gray edges on the picture, the blanking signal has a very fast rise time and a fast decay. Consequently, the blanking signal appears as a series of pulses, as indicated in Fig. 3-10. These are added to the video signal as the figure shows. Inasmuch as most pictures contain little or no truly black segments, the blanking signal is somewhat higher in amplitude than the video signal.

In addition to the blanking and video signals, other pulses are transmitted to synchronize the receiver deflection circuits to those of the camera. These synchronizing pulses should be invisible in the picture, so they are transmitted during the blanking interval. The only practical way in which this can be done

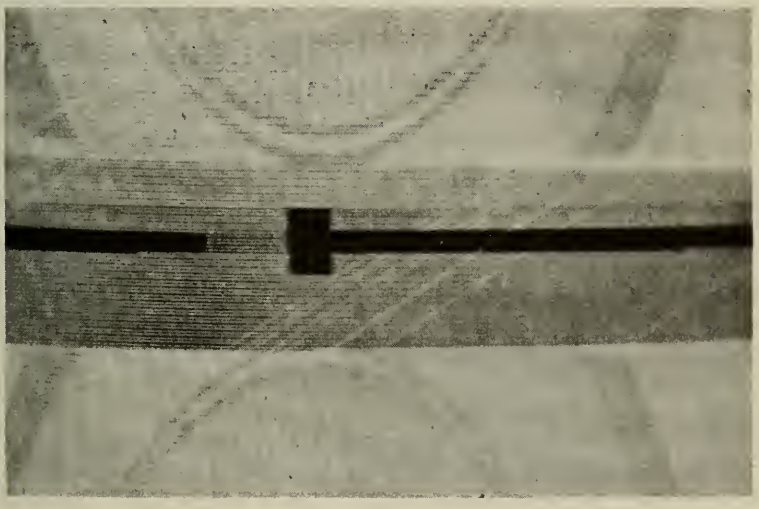


Fig. 3-12. Illustration of vertical blanking and sync on a TV receiver.

is to place the synchronizing pulses atop the blanking pulse, as illustrated in Fig. 3-11, a combined blanking and horizontal sync signal. Figure 3-12 shows how vertical blanking and sync would appear on a TV receiver screen.

Some interesting terminology appears in the composite pulse. The base, which is actually the blanking signal itself, is often referred to as a *pedestal*, since the synchronizing pulse is seated upon it like a statue. Looked at in a different manner, the sync pulse might resemble a house on a foundation. The interval between the leading edge of blanking and the leading edge of sync therefore becomes the *front porch* of the composite pulse. Naturally, the rear is

called the *back porch.* Horizontal synchronization in the receiver occurs at the leading edge of the sync pulse, and is accomplished by having retrace start at this time.

Figure 3-11 also illustrates the video signal as it is sent to the transmitter. The video signal has negative voltage peaks corresponding to white, while zero corresponds to black. In other words, black is more positive than white. This same relationship is maintained in transmission, but a d-c component is added to the signal to raise it above zero. The lowest point on the resulting wave is the white level, and the highest point, for obvious reasons, is termed the peak

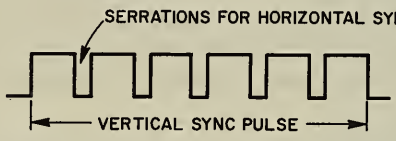


Fig. 3-13. A vertical sync pulse with serrations.

of sync. Basically, TV signals are transmitted in this fashion so that any large amplitude noises picked up by the receiver will produce black, rather than white, flashes in the picture. These are less annoying. This system of transmission is known as negative picture transmission, since application of this signal directly to a kinescope would result in a negative picture.

When the composite signal consisting of sync, blanking, and video information is fed into a modulator, it is the peak of sync that produces 100% modulation. Lower amplitudes, accordingly, produce lower percentages. Common practice is to discuss the signal in terms of these percentages. Thus, in the figure, the peak of sync is labeled 100%, the zero axis, of course, being 0%. On this basis, maximum white appears in the 15–20% region, while black lies at the 75% point. Pedestal level is merely another name for black level, the 75% value. From the figure, it is easily seen that all the video information lies within 55–60% of the overall signal range. Also of interest is the fact that the sync pulse is higher in amplitude than black level. When the signal reaches the kinescope, then, the sync pulse is "blacker than black", an appropriate phrase.

Vertical sync pulses are somewhat different from their horizontal relatives for the simple reason that the receivers must be able to differentiate between the two. Separation of vertical and horizontal pulses in the receiver is accomplished with circuits that are sensitive to the width of the pulse. If the vertical sync pulse is made substantially wider than the horizontal pulse, these circuits have no difficulty in separating them. This is entirely practical, for the vertical motion of the beam is 262½ times slower than the horizontal motion. The vertical sync pulse is therefore made 190 microseconds wide. This, however, is the same time as would be taken up by 3 horizontal lines, a fact that creates a problem. If horizontal sync is cut off for any time, there is a possibility that the horizontal oscillator might drift off frequency, and not be pulled back in

quickly enough when horizontal sync is again transmitted. To remove this possibility the vertical pulse is notched, or serrated, at half-line intervals. The serrations, being narrow, provide an equivalent horizontal sync pulse, while the overall width of the 6 wide pulses (Fig. 3-13) locks in the vertical circuits.

There is still another problem with vertical sync. The first field ends halfway through a line. The second field ends on a full line. In order that both vertical sync signals be identical, an additional set of 6 equalizing pulses is added both before and after the serrated vertical pulse. The equalizing pulses are spaced at half-line intervals, as shown in Fig. 3-14. Let us examine the figure in more detail.

At the top left of Fig. 3-14, the last few working lines of a field are shown. Slightly less than 0.5H (measurements in the diagram are all in terms of H, the time of one line, 63.5 microseconds) after the last working line has started, vertical blanking commences. Sitting on the blanking pulse at the left are the first 6 equalizing pulses. The first of these is a half line away from the start of the last working line. The second equalizing pulse is therefore a full line away from the last horizontal sync pulse. This second equalizing pulse provides horizontal sync, even though the beam is blanked out by the pedestal. The 4th and 6th equalizing pulses also provide horizontal sync, since they are one line apart. The vertical sync pulse now starts, and due to its half-line serrations, provides horizontal sync at the 2nd, 4th, and 6th notch. This is indicated by the arrows in the figure. Vertical retrace starts approximately at the end of the 4th vertical pulse, and continues for a period equal to several lines, the exact value depending upon the receiver. During the retrace period, the second set of equalizing pulses now lock in the horizontal circuits on the 2nd, 4th and 6th pulse. Between the 6th equalizing pulse and the first horizontal pulse of the second field, there is an interval of one line. The first horizontal pulse therefore appears at the correct timing interval to provide proper synchronization. At this point, too, retrace has usually been completed, and the beam is starting to move down. From 4 to 12 additional horizontal sync pulses are then placed atop the vertical pedestal to permit the sweep of the beam to become linear before blanking is removed.

At the end of the second field, vertical blanking and sync again take place. Now, however, due to the fact that the last working line is a full one, the first equalizing pulse appears at an interval of one full line from the last horizontal pulse. Horizontal sync in this field is then on the 1st, 3rd, and 5th equalizing pulses. After this, again due to the half-line separation between serrations, horizontal sync occurs at the 1st, 3rd and 5th notch in the vertical pulse. Again, vertical retrace starts at the end of the 4th pulse, and again takes several lines. The second set of equalizing pulses for this field also provides horizontal sync on the 1st, 3rd and 5th pulse, but the first horizontal pulse comes along only a half line after the last equalizing pulse, so it is once again in the correct position to maintain sync. Another 4 to 12 lines is added atop the pedestal to provide linearity, and then the blanking is removed. At the end of this field, the sequence starts all over again at the top left of the figure.

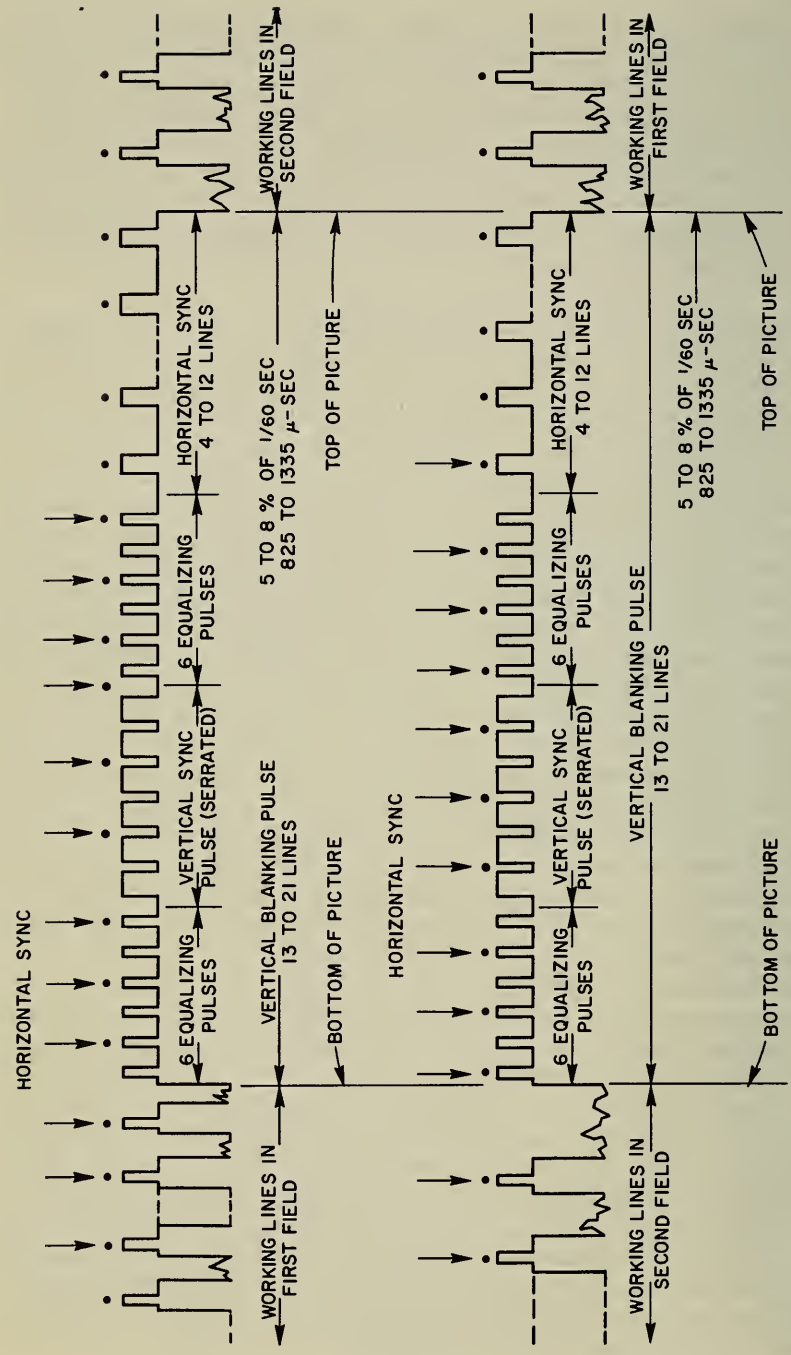

HORIZONTAL SYNC
6 EQUALIZING PULSES
VERTICAL SYNC PULSE (SERRATED)
6 EQUALIZING PULSES
HORIZONTAL SYNC 4 TO 12 LINES
VERTICAL BLANKING PULSE 13 TO 21 LINES
5 TO 8 % OF 1/60 SEC 825 TO 1335 μ-SEC
WORKING LINES IN FIRST FIELD
WORKING LINES IN SECOND FIELD
BOTTOM OF PICTURE
TOP OF PICTURE
HORIZONTAL SYNC
6 EQUALIZING PULSES
VERTICAL SYNC PULSE (SERRATED)
6 EQUALIZING PULSES
HORIZONTAL SYNC 4 TO 12 LINES
VERTICAL BLANKING PULSE 13 TO 21 LINES
5 TO 8 % OF 1/60 SEC 825 TO 1335 μ-SEC
WORKING LINES IN SECOND FIELD
WORKING LINES IN FIRST FIELD
BOTTOM OF PICTURE
TOP OF PICTURE

Fig. 3-14. Vertical and horizontal sync for two fields.

Television Station Equipment

Any technical discussion of TV would be incomplete without some examination of the equipment used in the studio. Figure 3-15 is a highly simplified block diagram of a typical TV station. The camera, of course, supplies the video signal. Camera outputs are relatively low, so a chain of video amplifiers is used to build up the signal. If more than one camera is used in the studio, switching circuits are added to permit selection of one camera at a time. A mixer circuit follows the amplifiers, and it is at this point that sync and blanking are added to

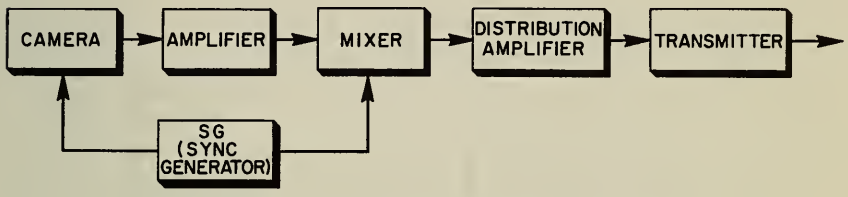


Fig. 3-15. Highly simplified block diagram of a TV transmitter.

the signal. The resulting composite video signal then goes to a distribution amplifier, a device that permits several circuits to be connected to its output, although this is not shown on the diagram. The block marked SG is perhaps the most important component in the installation, for this is the sync generator, the circuit that manufactures the sync, blanking and equalizing pulses, as well as another set, horizontal and vertical drive, used to lock in the deflection circuits of the camera.

Video amplifiers are similar to audio amplifiers in many respects, but there is one important difference: the bandwidth of the video amplifier is 4.5 mc. Due to this wide bandwidth, the amplification provided by any one stage is substantially less than that of an audio amplifier. Consequently, more stages are required to build a signal up to a sufficient amplitude.

As video signals pass through the chain of amplifiers, they center themselves on a zero axis. Up to a point this is permissible, but when the blanking pedestal is to be added, the black level of the signal has to be set equal to the pedestal level. This is accomplished with the aid of a *clamper*, known popularly as a *d-c restorer*. Briefly, a clamper locks (or clamps, hence the name) either peak of a wave to a predetermined voltage level. No amplification or distortion is present, and the wave is unchanged, except that a d-c component has been added.

After clamping, blanking is added to the signal in a mixer stage. A second mixer adds in the sync signal to the combination of video and blanking. The final output is then the composite signal.

Studio sync generators start out with a basic oscillator operating at 31.5 kc.

One output of the oscillator is sent to a series of pulse-forming networks to generate the equalizing pulses, since these occur at a 31.5 kc rate. A second output is delivered to a frequency divider that cuts the oscillator frequency in half, producing 15.75 kc. Pulse-forming circuits take this frequency and generate horizontal sync, horizontal blanking, and horizontal drive pulses. The 15.75 kc from the frequency divider is also fed to a chain of frequency dividers that drop the frequency down to 60 cps. Additional pulse-forming networks

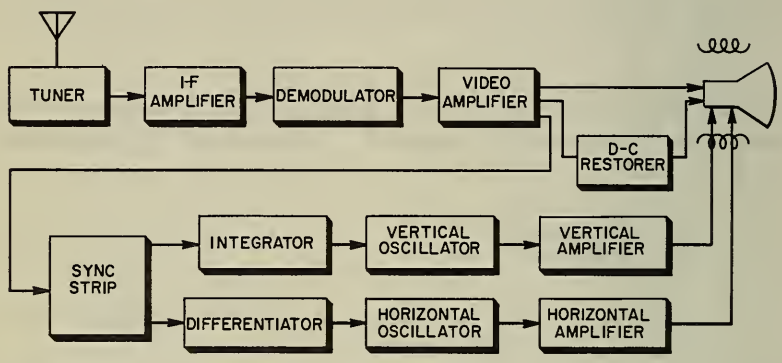


Fig. 3-16. Block diagram of a TV receiver.

now generate the necessary vertical pulses. Finally, the 60-cps signal from the divider is compared to the incoming 60-cycle a-c line. Should any difference exist between the two, a voltage is fed back to the oscillator, causing it to change frequency slightly, since it is assumed that the a-c line is extremely accurate.

TV Receivers

Television receivers are the last link in the chain of equipment used to reproduce pictures in our homes. A receiver contains four major groups of circuits, the tuner, the i-f amplifiers, the video circuits, and the sync and deflection circuits. Each group may be further subdivided, as the block diagram of Fig. 3-16 shows. For simplicity, only the video and sync and deflection circuits have been so separated, and even here, certain circuits have been eliminated. The tuner acts much in the manner of the r-f stage, oscillator and mixer of a standard superheterodyne radio, changing the incoming modulated signal to a lower frequency which is then amplified by the i-f system and passed on to the demodulator. All the r-f and i-f signal circuits are broadband systems, to accommodate the wide bandwidth of the video signal. The demodulator, too, is broadbanded, so that its output will include the high video frequencies essential to good resolution.

From the demodulator, the video signal goes through one or more video amplifiers. At the kinescope, the black level must be negative, so that it can cut off the beam during blanking. Each video amplifier, like its audio cousins, inverts the signal fed into it. Thus, the output polarity of the demodulator is determined by the kinescope requirements and the number of video amplifiers between demodulator and picture tube. In the event the video signal is fed into the cathode of the kinescope rather than the grid (a kinescope electron gun is similar to a tetrode), the polarity requirement causes black to be positive, but this is of no concern, since it merely requires the opposite polarity from the demodulator.

The video signal delivered to the kinescope contains sync and equalizing pulses, but inasmuch as these are blacker than black, they cause no trouble, and remain unseen. It is necessary, however, to ensure that the black level cuts off the beam. A d-c restorer is used for this purpose, usually placed directly before the kinescope. In more recent sets, the d-c restorer is incorporated into the kinescope itself, or the last video amplifier. Use of the restorer also ensures that white signals produce white, and gray signals, gray. In addition, the amount of the d-c component added to the signal by the restorer is proportional to the average background illumination of the scene being televised, and this d-c component may be used to act as additional bias on the kinescope to provide the proper contrast.

The deflection oscillators in television receivers do not normally generate sine waves, although in some older circuits they were permitted to do so. Most often, relaxation oscillators are employed. These circuits are tuned by resistance and capacitance rather than inductance and capacitance. The two most common relaxation oscillators are the *blocking oscillator* and the *multivibrator*, whose output waveforms are indicated in Fig. 3-17. The blocking oscillator consists of a tube, usually a triode, and a transformer that provides in-phase feedback between output and input. A pulse delivered to the input causes the circuit to start a new cycle if it has not already done so of its own accord. The multivibrator is a two-tube oscillator with the output of each stage feeding the input of the other. A free-running, or astable, multivibrator, oscillates by itself as soon as operating voltages are applied. The frequency and mark-space ratio of the output are determined by the time constants of the grid circuits. Changing these components changes both the frequency and the mark-space ratio. The free-running multivibrator may be triggered, or caused to start a new cycle, by narrow pulses. The "one-shot", or monostable multivibrator, on the other hand, is not an oscillator at all. When a triggering pulse is sent in to the one-shot multivibrator it goes through one cycle of operation, then stops and waits for the next triggering pulse. The frequency of the one-shot multivibrator, therefore, is dependent upon the number of pulses it receives per second. Its mark-space ratio, however, is determined by the grid circuit time constants. Another form of multivibrator is the "binary trigger", or Eccles-Jordan circuit. This circuit is similar to the one-shot, but requires two triggering pulses, one for the positive-

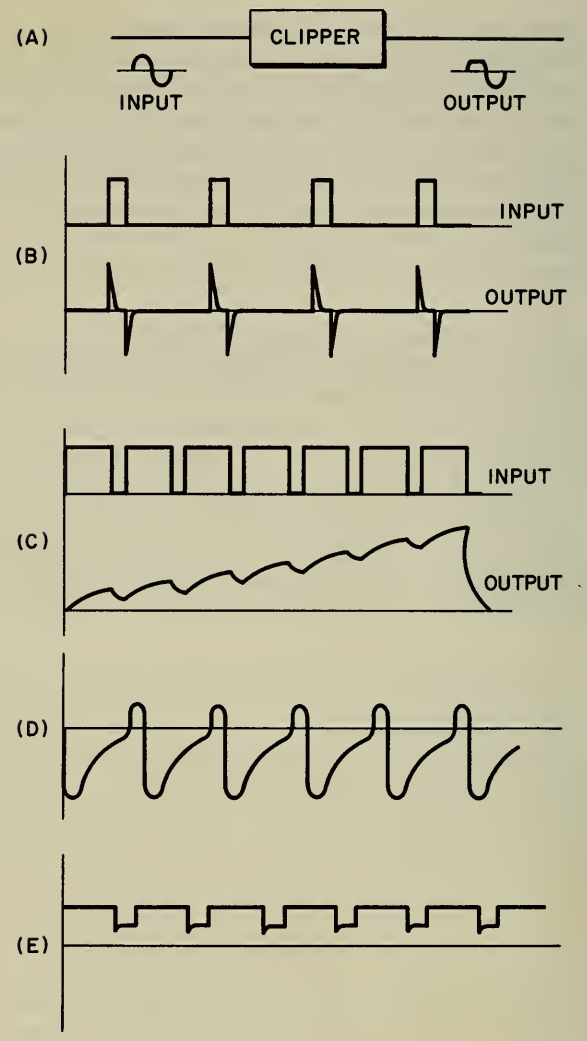


Fig. 3-17. (A) Action of a clipper. (B) Differentiated pulses. (C) An integrated pulse. (D) Blocking oscillator output. (E) Multivibrator-output waveform.

going portion of the output, another for the negative section. Both the frequency and the mark-space ratio of the binary trigger are therefore dependent upon the trigger pulses. Multivibrators are often used to provide time delays between input and output by altering the output wave to obtain pulses at a time fixed by the mark-space ratio. They are also used as frequency dividers.

Many modern television receivers use a combination of tuned circuit and relaxation oscillator in the horizontal circuits. This arrangement is known as *synchroguide.* In its most common form, the tuned circuit supplies a sine wave to a blocking oscillator to provide more accurate timing. Both sawtooth and pulse outputs are available from a synchroguide circuit, and it usually works in conjunction with some form of automatic frequency control.

The composite video signal delivered to the kinescope is also sent to a sync stripper, although some receivers use a different name for the circuit. Basically, the stripper slices off the sync pulses and passes them on, but discards the video information. In television and control systems, circuits that cut out sections of a signal above or below a predetermined amplitude level are known as *clippers.* Usually, they are diodes, although triodes or pentodes may be used if amplification is desired. Generally, clippers operate by either short-circuiting or open-circuiting the signal path at the chosen level, thereby permitting only a portion of the signal to pass. The action of a clipper is shown in Fig. 3-17, part A. Another form of stripping circuit is called a *limiter.* Actually, limiters do not slice. Instead, they act to reduce the peaks of the signal wave. Limiters are amplifiers, but they work with low operating voltages, causing cutoff and saturation to be very close to each other.

Sync pulses coming from the stripper are normally too small to be of use, so they are sent through an additional amplifier and on to a separator which divorces the horizontal and vertical pulses. In television receivers, separation is accomplished with the aid of a pair of R-C filters. One of these, the *differentiator,* so named because its output is proportional to the rate of change of its input, has a short time constant, and responds only to the horizontal and equalizing pulses, neglecting the vertical pulse except for the notches. The output of a differentiator is a pair of spikes, one positive, the other negative, corresponding in time to the leading and trailing edges of the input pulse, as shown in Fig. 3-17, (B). If the input pulse is positive, the first spike is also positive, the second negative. Conversely, if the input polarity is reversed, the first spike becomes negative. Differentiated pulses provide extremely accurate timing, since they are so short. The second filter, known as an *integrator,* has a long time constant, and produces practically zero output for narrow pulses. It takes the wide vertical pulses and provides an output proportional to the sum of their amplitudes, hence its name. An integrated vertical pulse is illustrated in Fig. 3-17, (C).

Regardless of the type of oscillator used, its output is sent to a shaping circuit to change the waveform into either a sawtooth or trapezoid, depending upon the circuits that follow. In practice, most shaping circuits are built into the oscillator circuits directly, thereby saving an added stage. The resulting waveform is then sent through an amplifier to build up the necessary power for deflection. The elapsed time between the arrival of a sync pulse in the oscillator and the start of retrace in the deflection coils is negligible, so the start of any line or field finds the appropriate signal waiting at the kinescope electron gun.

Color Television

The transmission of colored pictures by television represents a triumph of the art of packaging, for a color signal must contain much more information than that provided for monochrome (black and white) television, while still occupying the same bandwidth. To see how this packaging is accomplished, we must first understand color, what it is, and how it affects our vision.

Nature has created a marvelous device, the human eye, that permits us to observe our surroundings with the aid of what is called "visible light". Actually, visible light is electromagnetic radiation at astronomically high frequencies, extending from 3.85×10^{14} cps up to 7.9×10^{14} cps. Because these numbers are difficult to work with, light waves are more commonly measured in Angstrom units or millimicrons, the latter being 10^{-9} meters. With these units, visible light occupies a band between 380 and 780 millimicrons, as illustrated in Fig. 3-18. This spectrum, as it is known, may be broken up into smaller bands, each representing what is referred to as a color. At the low frequency (or longer wavelength) end of the spectrum, lie the reds. Moving towards the other end of the spectrum, red fades gradually into orange, followed in turn by yellow, green, cyan (another name for bluish-green) and finally, at the high end, blue. Each *hue,* the technical term for color, appears at a distinct frequency in the spectrum. Between the hues specified in the figure, there exists a multiplicity of

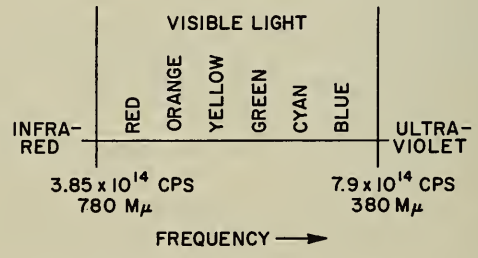


Fig. 3-18. The visible light spectrum.

other hues, each differing slightly from its neighbors. These in between hues need be of no concern to us, for they may be reproduced by combinations of the more important hues.

Examination of the human eye (Fig. 3-19) has disclosed that the retina consists of a vast number of tiny nerve endings sensitive to light. These endings are shaped peculiarly, either like a rod or a cone. The rods act as brightness perceptors while the cones are hue perceptors. There are three types of cones, one sensitive to red light, another to green, and the third to blue. Accordingly, these are known as the *primary* hues. Note their position in the spectrum. Note also, that between these primaries appear many other hues. Yellow, for instance, is

shown between red and green. When the eye is focused on a yellow object, both the red and green cones are stimulated. Clearly then, the eye is translating yellow into a mixture of red and green. Similarly, cyan appears to the eye as a mixture of blue and green. The eye also considers orange to be a mixture of red and green, but in this case there is more red in the mixture than green. It seems apparent from these results that any hue may be thought of as a mixture of

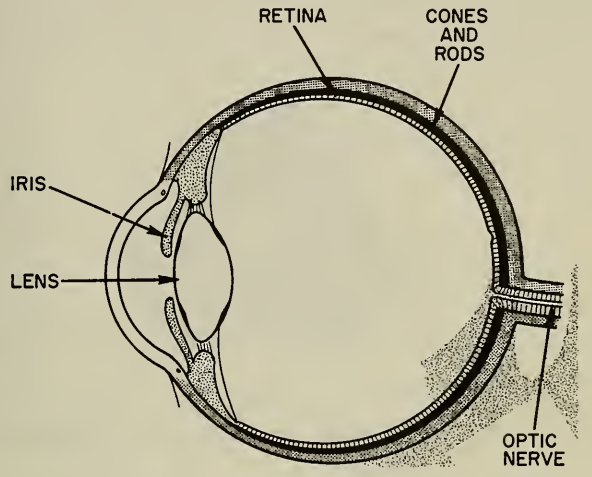


Fig. 3-19. The human eye.

primaries. The location of the hue in the spectrum determines the relative amount of each primary needed in the mixture.

A combination of all three primaries is also possible, this mixture giving rise to white. White is not considered to be a hue, since it is produced by radiation throughout the entire spectrum. Black, conversely, is the complete absence of radiation in the spectrum.

Simple combinations of primaries are often illustrated by a circular diagram such as that of Fig. 3-20. Where two primaries overlap, the hue of the mixture appears. For a triple overlap, white results. A hue at 180° from a primary is called the complementary of that primary. Patterns like that of Fig. 3-20 are created experimentally by projecting light of the three primary hues onto a screen. The light energies of the beams add to each other in the overlapping areas, and for this reason, a system using red, green, and blue as the primaries, is called an *additive* color system. The color kinescope, by virtue of its construction and operation, forms an additive color image on its screen. There are also subtractive color systems, used mostly in color printing, but these have no application in color television.

Let us now turn our attention to another aspect of color vision. Everyone

knows the sky is blue, but, how blue is it? Certainly, it is different from, say, a blue serge suit, yet both may be the same hue. In either case, the blue cones of the retina are stimulated. For the suit, only these cones receive any impression, while for the sky, all three cones are stimulated, the blue cone receiving somewhat more radiation than the others. But, any radiation affecting all three cones appears to be white to the eye. Thus, the light blue sky is seen to be a combination of blue and white. The amount of white mixed in with a hue is an inverse measure of the *saturation* of the hue. Deep hues (not necessarily dark) are said to be highly saturated, while pastel shades are lightly saturated, or de-

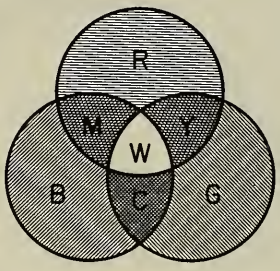


Fig. 3-20. Additive primaries and complementaries, including white.

saturated, hues. To illustrate, fire engine red is a highly saturated hue. The same hue, desaturated, is known as pink.

Saturation is measured on a percentage basis; 100% saturation indicates that only the one hue is present, and there is no contamination by white light. At the other extreme, 0% saturation is the complete absence of any hue. Only white exists at this level.

It is important to recognize that brightness and saturation are not the same. *Brightness* depends upon the total amount of radiant energy in the visible spectrum. *Saturation* is determined by the ratio of the radiant energy at one frequency, to the balance of the energy distributed throughout the spectrum.

From the preceding discussion, one fact emerges: To reproduce colored pictures, both hue and saturation have to be transmitted. Brightness information must go along with the color signal to complete the picture. It remains only to develop a method whereby these three components may be fitted together so that the color signal will appear as black and white to a monochrome receiver, while providing colored pictures in color receivers.

The visible light spectrum may be redrawn to reveal both hue and saturation simultaneously. This is done by bending the spectrum around into roughly a horse-shoe shape. The result, illustrated in Fig. 3-21, is known as a *chromaticity diagram*. In this diagram, green appears at the top, red to the right, and blue in the lower left corner. Complementaries, too, are shown in the figure. A line

is added to close the open end of the figure, connecting together red and blue. (The X and Y axes are used merely for locating particular points.) Brightness information does not appear in this type of chromaticity diagram.

In the chromaticity diagram, the edges represent 100% saturation. The

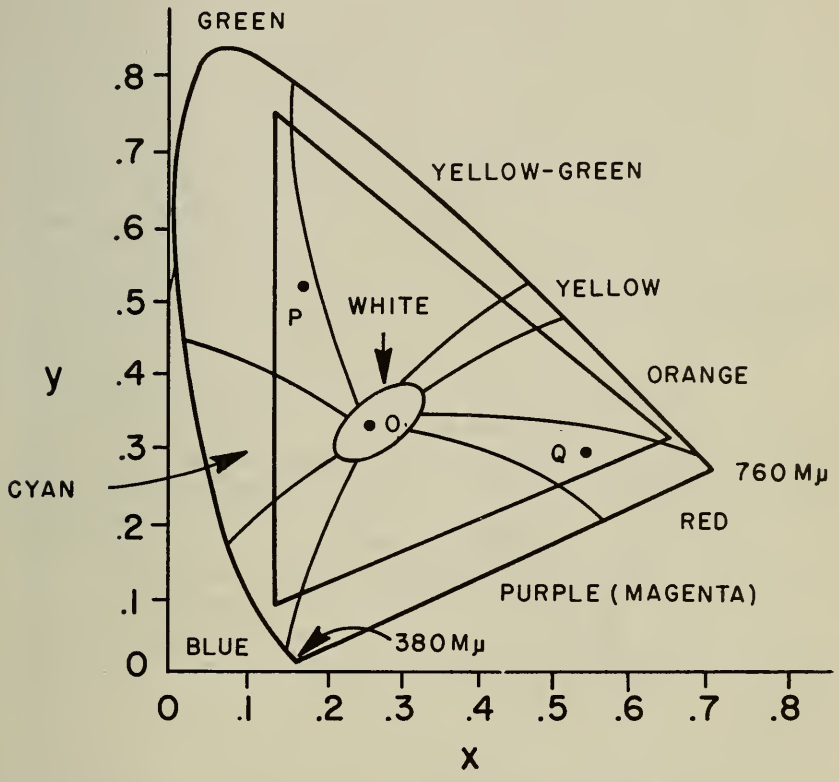


Fig. 3-21. Chromaticity diagram.

center, indicated by a zero, is 0% saturation. A point within the figure indicates both hue and saturation by its position. For example, point P is located on a line between the center and the green region. The hue is therefore green. Furthermore, starting from zero, point P is located at 0.4 of the distance between the center and the edge. Hence, the saturation level is 40%. Similarly, point Q in the diagram denotes 60% red. For technical reasons, the color TV system cannot reproduce 100% saturation of all hues. It is limited to the saturation levels inside the triangle shown in the diagram. Nevertheless, this is more than

sufficient, for these levels exceed those of both color photography and color printing.

Suppose that a set of coordinate voltage axes is added to the diagram, as in Fig. 3-22. Positive voltages will be measured in the usual manner, either up or

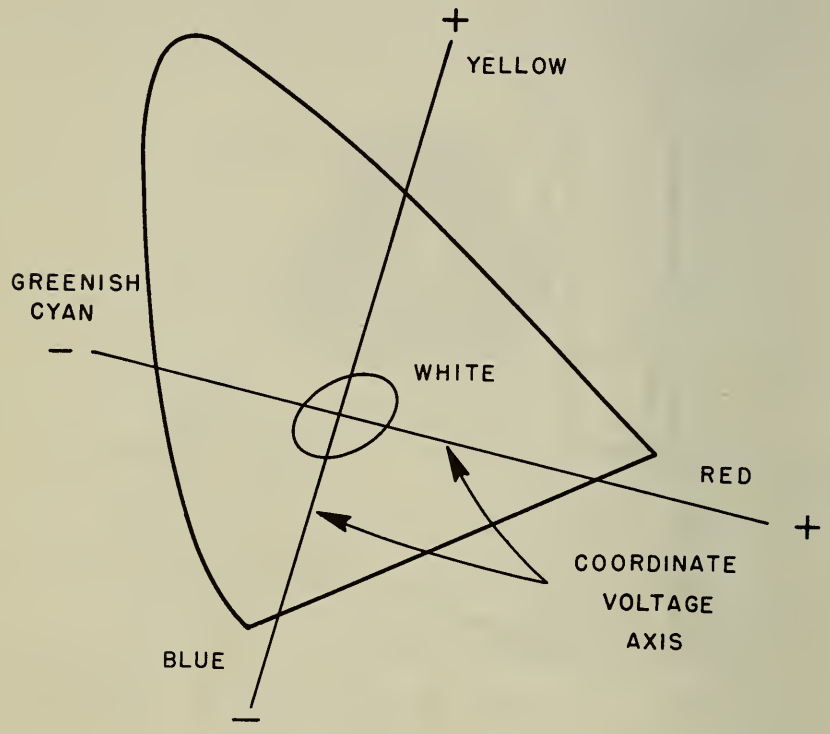


Fig. 3-22. Addition of voltage-coordinate axes to a chromaticity diagram.

to the right, larger values appearing farther from the center than low values. Red, then, is a positive voltage, as is yellow. Conversely, both cyan and blue are negative (in fact, cyan is sometimes called —red). It seems clear that the hues, or their voltage equivalents, are now being represented as phasors, since any lines drawn from the center to points within the diagram have both magnitude and direction. It is clear, too, that the length of the phasor is proportional to both the voltage amplitude and the percentage of saturation. This being so, voltage amplitude may be used to transmit saturation information in the color system.

Hues other than blue, cyan, red and yellow, may also be translated into volt-

ages. Magenta, for example, is known to be a combination of red and blue. Voltages along both axes may be added together to provide a voltage for magenta, provided only that they are added 90° out of phase with each other, inasmuch as red and blue are separated by that amount. Note that if small amounts of red and blue are used, the resulting phasor will be low in amplitude. Thus, low saturation magenta is a combination of low saturation blue and low saturation red. The phasor lengths remain proportional to saturation.

Let us now choose an arbitrary zero reference axis for the phasors. Assume, for discussion purposes, that the axis through the red region is called 0°. With respect to this axis then, yellow appears at 90°, cyan at 180°, and blue at 270°. All other hues are situated at some angular position in the diagram, and may be expressed in degrees using red as the reference. Each hue in the spectrum is defined by a phasor having some angular displacement from the reference. A phasor however, merely symbolizes a phase difference between alternating voltages. If voltages are used to transmit the color information, *the phase angle of the signal voltage with respect to the arbitrary reference defines the hue.* Summing up, then, we find that hue and saturation may be transmitted by signal voltages, the saturation component being determined by the phasor amplitude, and the hue by the relative phase angle.

Before proceeding with the development of the color signal, it is necessary that we first examine another factor related to the transmission of colored pictures. This is the problem of compatability. Expressed simply, compatability means that a monochrome receiver has to produce an acceptable black and white picture from a color signal, and a color receiver has to produce acceptable black and white when color is not being transmitted. The first requirement is easily met by the color system, since a brightness signal, equivalent to monochrome, is normally transmitted in any event. The black and white receiver utilizes this signal only. The second requirement is tied in with the operation of the color kinescope. To create all possible hues on the kinescope screen, the three additive primaries have to be present. Thus, three phosphors are needed, one for each primary. These are printed on the screen in an intricate dot pattern so that a group of three dots is always available to reproduce any possible combination of the primaries. At the kinescope neck, three electron guns are mounted, one for each primary. The beam from the "red" gun is permitted to strike only the phosphor dots that glow red. Similarly, the blue and green guns hit only the appropriate dots. Black components in a picture are easily formed by merely cutting off all three guns. On the other hand, white is created by activating all three guns simultaneously. Due to the radiant energy characteristics of the three different phosphors, a specific ratio of voltages for red, green, and blue must appear at the guns in order to produce the same white on a color screen as that seen on a standard monochrome kinescope. When monochrome is transmitted, the signal is fed to the three guns of the color kinescope through a voltage divider, known as a *matrix.* The matrix delivers 59% of the incoming signal to the green gun, 30% to the red gun, and the remaining 11% to the blue gun.

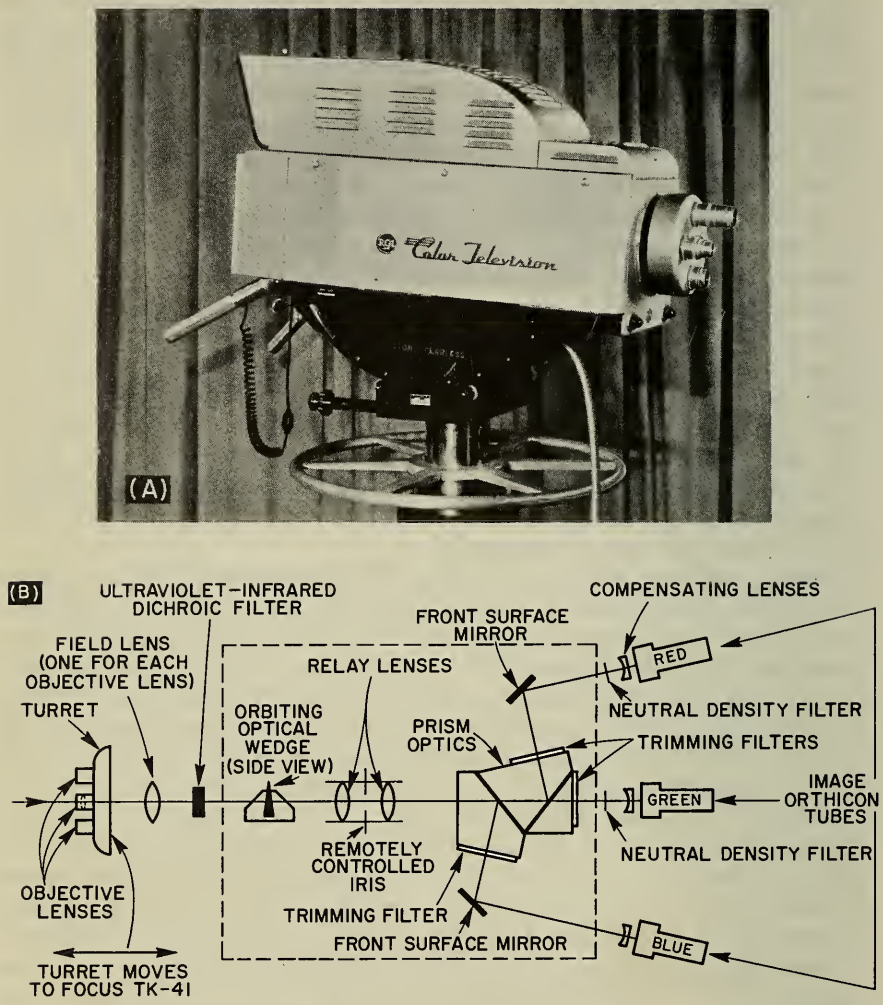


Fig. 3-23. The color camera (A), showing the mirrors and image orthicon locations (B). *Courtesy RCA.*

Suppose we now examine the color camera (Fig. 3-23) and associated equipment to see how the color signal is generated. Outwardly, the color camera seems to be much the same as the monochrome camera. Inside, however, there are three camera tubes operating in conjunction with mirrors and optical filters. One of the tubes is made sensitive only to blue, another only to green, and the third, to red. Any object being photographed is resolved into combinations of the three additive primaries. Outputs from the three tubes are sent simul-

taneously to a matrix, in this case a combination of mixer and voltage divider. The matrix takes 59% of the green camera output, 30% of the red camera output, and 11% of the blue camera output, and adds them together. Observe that these are the same percentages used to divide up the monochrome signal

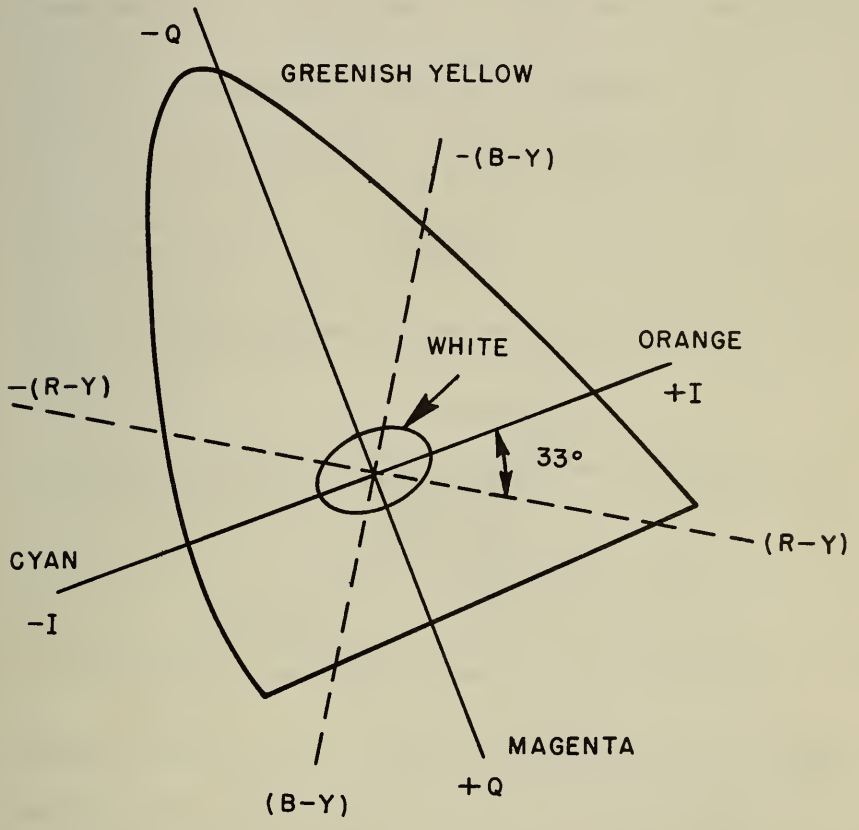


Fig. 3-24. Chromaticity diagram using orange-cyan as a reference phasor.

for distribution to the guns of a color kinescope. The combination is therefore a monochrome, or brightness, signal. In color TV, it is designated the *luminance* signal and is given the symbol *Y*.

Now, let us return for a moment to our chromaticity diagram (Fig. 3-22). Analysis of the color components in terms of camera voltages shows that the hue produced along the positive horizontal axis is almost the same as that obtained by subtracting the *Y* signal from the output of the red camera. For convenience, this is known as (*R-Y*). Geometrically, the hue in the negative

direction along the horizontal axis must then be $-(R\text{-}Y)$. Similar analysis for the vertical components indicates that subtracting Y from blue, creating $(B\text{-}Y)$, is close to the axis value of blue. Yellow is then close to $-(B\text{-}Y)$. Since the Y signal is derived in the matrix, it is not too difficult to add extra parts to the circuit to subtract the Y signal from the camera voltages. One method in use is deceptively simple. The Y signal is passed through an amplifier to invert it,

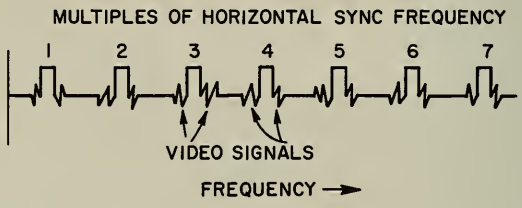


Fig. 3-25. Monochrome TV frequency distribution.

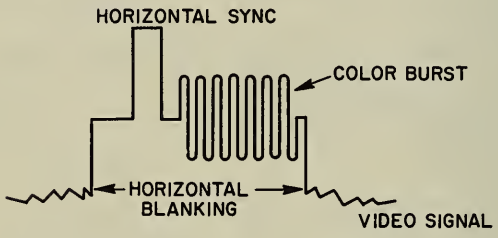


Fig. 3-26. Color burst added to the back porch of horizontal blanking.

creating $-Y$. This is then added to the R signal from the red camera, producing $(R\text{-}Y)$. $(B\text{-}Y)$ is obtained in a similar manner.

Research has shown that the human eye cannot resolve the hues associated with fine details or distant objects, which are seen as shades of gray. These components of a picture correspond to video frequencies above 1.5 mc. Since the eye cannot see them except in black and white, it is useless to transmit color information above this video frequency. Medium sized colored objects, corresponding to video frequencies between 0.5 and 1.5 mc are seen by the eye as either orange or cyan, at a saturation level determined by the object. In this region, then, it is only necessary to generate a signal proportional to the saturation of either orange or cyan, and transmit this along with the brightness component. For large objects and broad details, represented by video frequencies below 0.5 mc, the eye perceives all three primary hues. Color reproduction below this frequency therefore requires that both hue and saturation information be transmitted along with the brightness.

Now, if the eye sees medium detail as a mixture or orange and cyan, there is no point in transmitting $(R\text{-}Y)$ and $(B\text{-}Y)$. Matters may be simplified enormously if the axes originally used (Fig. 3-22) are rotated 33°, as in Fig. 3-24, so that orange and cyan form the ends of one axis. This is done in the color system when the color signals are added to the brightness, or monochrome component.

Monochrome video signals appear in clusters around multiples of the line-scanning frequency, 15,750 cps, as illustrated in Fig. 3-25. Blank spaces are visible between the clusters, and these provide a perfect place to park the color signals, since they cannot then interfere in any way with the standard black and white transmission. In order to fit the color signal into these slots, the $(R\text{-}Y)$ and $(B\text{-}Y)$ signals are made to modulate a subcarrier operating at 3.579545 mc. This frequency is exactly in the middle of a gap between two clusters, so the resulting color clusters fall into the holes between the black and white groupings. The $(R\text{-}Y)$ signal modulates the subcarrier directly while the $(B\text{-}Y)$ signal is permitted to modulate the subcarrier only after it has been shifted 90° in phase. This places the $(B\text{-}Y)$ component 90° out of phase with the $(R\text{-}Y)$ component, thereby providing the necessary coordinate axes at right angles to

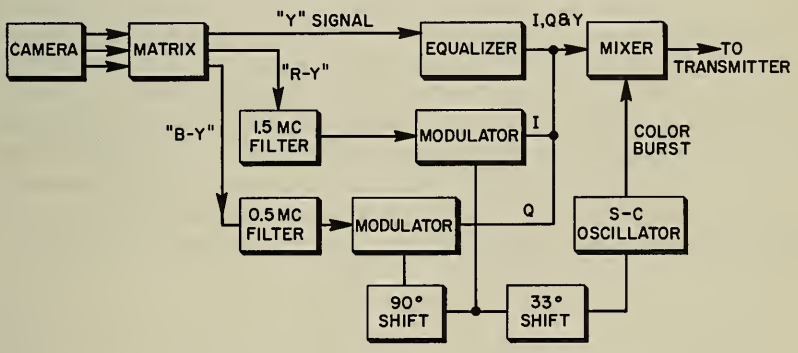


Fig. 3-27. Highly simplified block diagram of a color transmission system.

each other. The two modulated signals are added to each other in such a manner that the subcarrier itself disappears, leaving only its sidebands. At the receiver, the subcarrier must be added back into the color signal, and this is done by a special subcarrier oscillator. If color accuracy is to be achieved in such a system, both the frequency and relative phase of the receiver subcarrier oscillator must duplicate that of the subcarrier at the transmitter. It is therefore necessary to transmit an additional sync signal to lock in the subcarrier oscillator. This pulse, known as a color burst, consists of 8 or 9 cycles of the subcarrier frequency itself, placed on the back porch of each horizontal sync pulse, creating a composite horizontal pulse as shown in Fig. 3-26.

Figure 3-27 is a block diagram of a typical color transmitter. The three camera outputs feed the matrix. From the matrix Y, $(R\text{-}Y)$ and $(B\text{-}Y)$ are obtained. The $(R\text{-}Y)$ signal goes through a filter passing only those frequencies below 1.5 mc. Similarly, the $(B\text{-}Y)$ signal is filtered to remove all frequencies above 0.5 mc. The two signals are then sent to the modulator circuits where they are impressed on the subcarrier. In order to provide an orange-cyan axis, the modulated outputs provided by these two color difference signals ($R\text{-}Y$ and $B\text{-}Y$) are shifted 33° which, for convenience, is indicated by the block between the subcarrier oscillator and the modulators, although a somewhat different method is employed in practice. The $(R\text{-}Y)$ component then modulates the shifted subcarrier directly, but the $(B\text{-}Y)$ signal is applied only after an additional 90° shift of subcarrier phase. Due to the filtering and shifting of phase, the two color difference signals can no longer be termed $(R\text{-}Y)$ and $(B\text{-}Y)$. Instead, they are now referred to, respectively, as the I and Q signals, I indicating a signal that is in phase, or nearly so, with the Y component, while Q signifies a quadrature (90°) relationship to Y. I and Q are added together to form a *chroma*, or color signal, which is then combined with the Y component for transmission.

The subcarrier oscillator also provides a color burst which is fed directly to the transmitter. Since this burst goes along with the video signal, it may be used in the receiver as a reference phasor, to which the received chroma signal may be compared. Hue is therefore determined in the receiver by the phase relationship between the chroma signal and the burst. Saturation, of course, is given by the amplitude of the chroma signal, and brightness by the Y signal. Due to the filters, below 0.5 mc both I and Q are present, providing both hue and saturation information. From 0.5 to 1.5 mc, only the I signal appears, indicating the saturation level of the orange-cyan component. Above 1.5 mc, chroma signals are absent, and the receiver operates with only the Y signal.

Chapter 4

MECHANICS OF RECORDING

The word "recording" means, fundamentally, the process by which we store information, much as a warehouse stores goods. The type of information stored may fall into any one of many categories, math tables, symphonies, legal decisions, and so on. Books, motion pictures, and even letters, are recordings in a sense, but recording today has come to mean only the storage of audible sounds or visual effects. For the recording to be useful it must, or course, be available for future listening or viewing.

All recordings share a common trait in that they are based upon the "freezing" of a time-sequential signal. Moreover, it is insufficient for the recording system to merely freeze or lock the signal into a pattern. It must also be able to "defrost" the information and send back the same signal as that originally recorded. Not only must cycle follow cycle, but the time of each cycle, the time between successive peaks, troughs, pulses and wave trains, all have to be identical to that supplied to the recording mechanism. To illustrate, consider a vocalist sounding a note, say middle *C*. If the note was held for one second, there would be 256 distinct bits of information, each bit comprising one cycle of the sound being heard. Suppose now, that our vocalist decides to vary the sound he is producing, and in rapid succession, sings low *C*, middle *C*, and high *C*, each lasting for about 1/3 second. The sequence of information produced would be approximately 43 cycles of low *C*, 85 cycles of middle *C* and 171 cycles of high *C*. Listening to this vocalist in a concert hall, involves listening to and interpreting, each bit of the sequence. Now, if a recording of the sequence is to be made, it becomes necessary to build a mechanism that will take down the sequence in its proper time relationship, and store each bit in order. For playback, the mechanism has to reproduce 43 cycles of low *C* in 1/3 of a second, 85 cycles of middle *C* in the next 1/3 of a second, and 171 cycles of high *C* in the final 1/3 second.

Failure to create the exact number of cycles in the correct time interval means the playback is not the same as the original, and distortion exists. A simple experiment will show what happens if timing is wrong. Play a 45-rpm record at 33-1/3 or 78 rpm, and observe the result.

Disc Recording

To see how a recording system operates, suppose we examine the phonograph process in detail. The turntable in a record player provides a constant rotational velocity for the record placed upon it. Thus, it permits the timing sequence established in the studio to be recreated at home. The record itself consists of a disc containing a spiral groove which may start at the outer edge and continue towards the center for several inches, or it may start at the center of the record and travel towards the edge. Modern recordings are of the former type. In any event, the groove is the important thing on the disc, for it carries the information in the form of changes in the groove walls, called *modulations* (Fig. 4-1). For convenience, consider the groove as if it were a straight path as illustrated in Fig. 4-2, rather than part of a spiral. Observe that the walls of the groove slope down towards each other, and that at the top they are parallel and form a straight

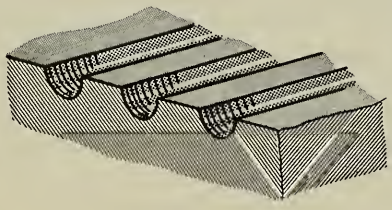


Fig. 4-1. Typical modulated grooves in a disc.

Fig. 4-2. Groove structure of a disc recording.

line. If a signal is now recorded in the groove, the shape of the groove does not change, but the walls bend away from their previous position, still staying parallel to each other. When a reproducing stylus (or needle) is placed in such a groove, and the groove is forced to move past the stylus, the stylus follows the variations embedded in the groove walls, and in turn, causes a voltage to be developed proportional to the amount of displacement of the groove wall from its normal center position. The frequency of the generated voltage depends upon the rapidity of the changes in the groove wall.

Consider now, the problems involved in making the original record from which the pressed copies we buy, are duplicated. Again, a turntable and motor

provide the rotational velocity required, but in this instance, a completely blank disc, containing no grooves, is used. The cutting needle cuts the grooves into the disc as the surface slides by beneath it. If nothing is being recorded, no information is delivered to the cutter, and the groove walls come out blank. When signals do appear at the cutter, however, the needle vibrates at right angles to the groove motion, and causes the groove walls to shift their position relative to their normal center. Large signals (representing loud sounds) cause

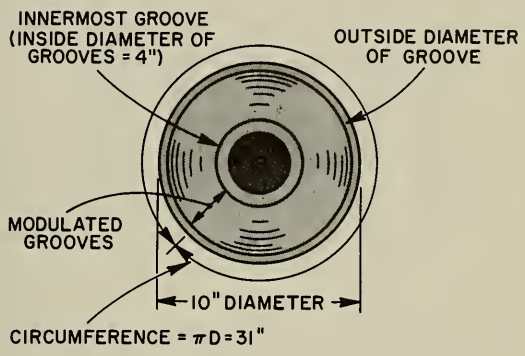


Fig. 4-3. A typical 10-inch phonograph record.

a substantial displacement of the groove walls, whereas soft sounds cause little displacement. Very soft sounds, then, are often wiped out in the recording process, for they produce practically no modulation of the groove walls. Very loud sounds, on the other hand, are dangerous, for they may cause the needle to cut into an adjacent groove. This cannot be permitted, so it is a common practice to limit the needle excursions in order to prevent over modulation of the groove. These two conditions, under and over modulation, place a limit on the *dynamic range* (or loudness range) which a disc recording can handle, determined by the minimum and maximum needle excursions.

A more serious problem with disc recording is the change in the frequency response capabilities as the groove moves toward the center. A 10-inch phonograph record, for instance, has a spiral path almost 31 inches long at the outside edge of the record, as shown in Fig. 4-3. Assume the record rotates at 78 rpm. If a continuous 1000-cycle note is to be recorded on this outermost groove, then in 1/78 of a minute (or 0.77 seconds) the entire 31 inches is traversed by the needle which follows the groove, and 770 cycles of the note will be recorded. Thus, each cycle occupies 31/770 inches along the groove. Suppose now, that the grooves take up 3 inches of the disc, radially. Then the innermost groove has a diameter of only 4 inches, which means that the length of the spiral path at this point is approximately 12 inches. Recording the same 1000-cycle note on the innermost groove causes each cycle to now occupy only 12/770 of an inch.

Note that the same number of cycles take up less linear length than they did at the outer edge. Although the record revolves with a constant angular (or rotational) velocity, the linear velocity of the needle-groove combination decreases towards the center as the spiral length decreases. This causes difficulty when high frequencies are to be recorded, for we reach a point where the grooves themselves cannot handle such tightly packed bits of information. Therefore, if it were possible to record 10 kc at the outer edge of a disc, it might not be possible to provide better than, say, 8 kc at the inside. One cure for this condition is to use a smaller width groove permitting more grooves to appear in less space. To obtain the same recording time, then, the innermost groove has a larger diameter. Modern recordings, the 33-1/3 and 45 rpm types, are made in this manner.

Another deficiency of the disc record can be traced to the needle, and the work it must do. In disc recording, it would be helpful if equal amplitudes produced equal displacements of the groove wall, regardless of frequency. However, the mathematics of dynamic moving systems shows that this is not possible. Generally, as the frequency applied to a mechanically moving system increases, the displacement decreases. A recording needle fed with a 500-cycle note might produce a displacement of 1/100 of an inch, but if the same mechanism were supplied with a 5000-cycle note, the displacement would be only 1/1000 of an inch. Clearly, then, this represents a problem when we attempt to record high frequencies. The solution is simple: we merely need to increase the drive to the cutter as the frequency increases, in order to compensate for the decrease in displacement. In fact, modern recordings do just that, but alas, how much power can be used to drive the poor needle? If it takes 10 watts of power to provide sufficient groove modulation at 1000 cycles, then approximately 200 watts at 10 kc are needed to obtain similar results. At present, using the standard recording curves, 40 kc represents a practical upper limit for disc recordings.

Optical Recording

Motion-picture sound has been recorded optically for more than 30 years. Optical recording systems translate the sound into a series of light and dark sequences that are photographically placed on a narrow track at the edge of the film. For playback purposes, a beam of light is passed through this track and on to a photoelectric cell. The variations in light intensity as the film is passed rapidly in front of the photoelectric cell perform the same job as the groove walls of a disc.

Optical film recording has several advantages over disc recording, foremost among them being the complete absence of moving parts in the playback system. Only the film moves past the photoelectric cell, so due to this lack of mechanical components, it becomes somewhat easier to play back higher frequencies. In addition, no inside or outside diameter need be considered, as the film, in any event, moves past the pickup point at a constant linear speed. In

fact, the only detrimental component of a film-recording system is the device used to produce the optical track.

Film tracks are made with either a light valve, or a galvanometer fitted with a mirror. The light valve controls the amount of light striking the film from a fixed unvarying source, producing what is known as a variable-density sound track. Galvanometer systems also use a fixed light source, but it is focused on the mirror. As the mirror vibrates in accordance with the galvanometer signal, a thin beam of light moves back and forth across the track. The resulting pat-

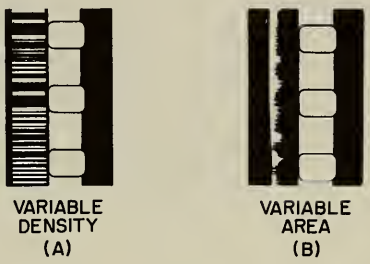


Fig. 4-4. Sound tracks: (A) variable density. (B) variable area. *Courtesy Westrex Corp.*

tern is called a variable-area track. Both types of track are illustrated in Fig. 4-4. Both systems use mechanical components having mass and inertia, and consequently present problems with regard to higher frequencies, just as the phonograph needle does.

Summarizing the above, it is apparent that two major drawbacks appear in disc recording, and one also appears in film work. Any newer system should attempt to avoid these pitfalls and must therefore meet two specifications: 1) the recording medium, film, tape, paper, or whatever it may be, should travel with a constant linear velocity past the recording device and playback pickup. This serves to make the frequency response independent of the length of the recording; and 2), neither the playback nor recording mechanisms should have mechanically moving parts, thereby eliminating the loss of high frequencies due to the system components.

Magnetic Recording

The magnetic recording system which is currently popular overcomes the limitations of the disc and optical systems to a certain extent, but has limitations of its own. Magnetic systems utilize thin plastic tape substantially similar to the Cellophane tape used for sealing packages, but it is much tougher. A thin layer of pulverized iron oxide is coated on the plastic base, and the signal is recorded by changing the magnetic pattern of the iron-oxide molecules. In a tape re-

corder, only the magnetic patterns of the oxide are altered. This is done by passing the tape through a varying magnetic field whose changes in strength and direction correspond to the signal being recorded. To record a signal on tape no mechanical motion of components is required, since the magnetic fields may be varied by passing changing currents through fixed coils.

The magnetic tape-recording system offers advantages over its earlier rivals, but it also poses problems. For example, high frequencies are affected by the dimensions of the playback heads, and therefore a limit exists here, just as in other systems. Further, the tape itself must be carefully manufactured so that no large oxide particles appear in the coated surface. The tape base must be able to withstand a substantial strain, and for this reason, as mentioned previously, the best tape is made of Mylar, a very tough film-like material. In order to provide sufficient time for a recording, the tape must be thin, so that more than 1000 feet may be spooled onto a reel no larger than 7 inches. Additionally, magnetic recorders have a somewhat restricted frequency range, as we shall see later on.

Transport Mechanism

Magnetic recording tape, like film, must be moved past a recording head at a constant speed. In film work, this is accomplished with rotating sprockets that engage holes in the side of the film, causing the latter to move. Magnetic tape uses no such sprockets or sprocket holes, and the tape is moved by passing it between two rotating wheels. Friction between the wheels and the tape prevents slippage in this system, and a constant speed is attained. The motors that drive the rotating wheels and the tape spools, together with the necessary tape guides, make up what is called a *tape-transport mechanism* or *tape deck*, whose function is to take tape from a storage reel, pass it in front of the recording and pickup heads, through the driving wheels and onto a take-up reel. Electrical circuits included in a tape transport are those that supply power to the motors, and relays that may be used for operating the equipment.

Figure 4-5 shows a typical tape-transport mechanism, with the supply reel to the left. From this reel the tape unwinds in a counterclockwise direction, and passes, as the dotted line shows, around an *idler post*. Idler posts serve to smooth out small variations in the tape speed as it comes off the supply reel, for tape has a tendency to stick, and may not feed smoothly from the reel. The idler, or *stabilizer arm*, as it is sometimes called, also acts as a guide for the tape, keeping it a fixed distance from the base board, and preventing any vertical motion of the tape as it moves on to the heads. After passing through the stabilizer the tape moves to the recording and playback *heads*. Depending upon the price and application of the machine, there may be anywhere from 2 to 5 heads, all enclosed in a shield called a *head cover*. To ensure good contact with the heads, pressure pads are sometimes used to hold the tape in position. In more expensive machines, the tape path past the heads is curved, causing the tape to lie

against the heads, thereby eliminating the need for pressure pads. Generally, the first head with which the tape comes into contact is the *erase* head, which serves to remove any previously recorded signals or noise that may be on the tape before making a new recording. In playback the erase head is disabled and has no effect. The second head may be a combination record-playback unit, or just a record head. Home-type machines use a dual purpose unit, while more expensive machines have a third head used for playback only. Use of three heads

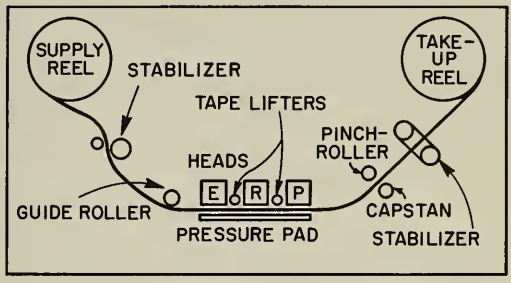


Fig. 4-5. Tape-transport mechanism.

(separate record and playback heads) permits monitoring from the tape during recording.

After the tape has passed through the heads, it may encounter another guide roller, used to maintain accurate positioning of the tape against the heads, or it may go directly to the driving mechanism. This consists of the rotating wheels mentioned above. Actually, only one of these rollers, called the *capstan*, is driven by a motor. The capstan is a metal shaft, machined to a very smooth surface, with a heavy flywheel mounted on it underneath the deck to provide inertia, and help reduce speed variations. Near the capstan is another wheel, rimmed with rubber, and mounted so that it is free to swing into contact with the capstan when desired. The *pinch-roller*, as it is known, pinches the tape between its own surface and that of the capstan when the machine operates, and in this manner imparts the capstan's motion to the tape. It is important that the pinch-roller be held firmly in place during operation of the machine, so that no slippage of tape occurs.

Following the capstan and pinch-roller, professional machines provide an additional stabilizer arm that serves to take up slack between the capstan assembly and the take-up reel. When tape is first started through the machine, there is a tendency for the take-up reel to jerk, and even when running it is possible for the take-up reel to vary slightly in speed. The stabilizer arm protects against speed variations of the take-up reel that might snap the tape, or change its speed. Also, the rear stabilizer arm is mechanically linked to a switch to turn off the motors if the tape should break. Finally, the tape spools itself onto the take-up reel.

After a recording has been made, the tape must be rewound in order to have it ready for playback. In this mode of operation high speed is desired, so the capstan and pinch-roller are separated, and the original supply reel is rapidly driven in a clockwise direction, pulling the tape off the take-up reel. Most semi-professional and professional machines will rewind 2500 feet of tape in less

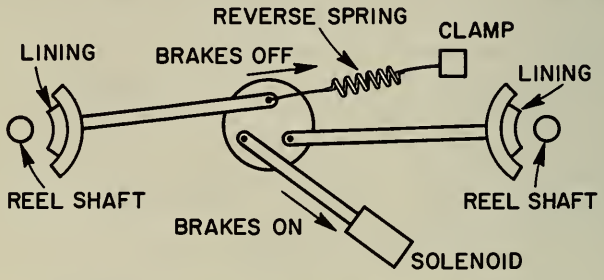


Fig. 4-6. Typical braking system for a tape recorder.

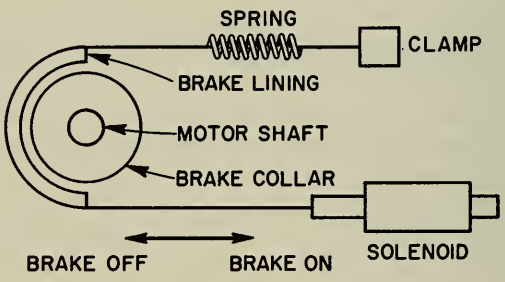


Fig. 4-7. Improved form of a tape-recorder brake.

than a minute, while home-type machines take somewhat longer. When tape is being rewound at high speed, it is a good idea to provide some "drag" on the system, since slight speed variations in the supply reel may cause tape to spill over, or snap. The drag allows the tape to wind tightly, under tension, on the supply reel. Keeping tape under tension on the supply reel prevents it from spilling out or breaking when it is again fed into the machine for playback purposes, and is an aid in maintaining constant speed.

The magnetic material on the tape resembles a very fine sandpaper, or crocus cloth. Thus, as the tape passes over the heads during recording and playback it grinds away at their surfaces, and eventually causes these surfaces to wear down. It would seem, too, that if the tape were permitted to remain in contact with the head surfaces during rapid rewind, the head wear would be increased tre-

mendously. In practice, however, this is not the case, for as the tape moves at high speeds it swallows air at the normal rubbing surfaces, creating an air film which protects the head. Before this was known, quite a few professional machines provided a device known as a *tape lifter*, to push the tape off the heads during fast operation. Lifters are usually thin rollers mounted on thinner shafts positioned by a solenoid and springs. During recording and playback the lifters are retracted into the spaces between the heads. In simpler machines, lifters are not used, but guide bars or rollers are provided at the two ends of the head assembly. Normally, the tape is guided by these devices so that it does not make contact with the heads, but during recording or playback, close contact is essential. This is accomplished by having a pressure pad push against the tape, forcing it onto the heads. Pressure pads add drag to the tape during record or playback, and make the work of the capstan and pinch-roller that much harder. For this and another reason discussed below, pressure pads are not used in professional machines.

Transport mechanisms must also have some device which stops the tape and the two reels when desired. Consider what might happen if, to stop the machine, only the pinch-roller were disengaged and the motors disconnected. The take-up reel would continue to rotate, as would the supply reel, until friction eventually stopped them. Depending upon the inertia possessed by these reels the tape might snap, or, as is more likely, it would come off the supply reel and spill onto the floor. Clearly, a braking system is needed to prevent these occurrences. Home-type machines, in which the reels are driven by belts, use the belts themselves to provide braking action, which is therefore not too good. Some machines utilize the tape to aid in braking, since one reel will drag against the other. Professional machines use a braking system similar to that in an automobile, although not hydraulically operated. Simply, a pressure block, containing a piece of brake lining material, is placed close to the reel shaft. When the machine is to be stopped, mechanical levers or solenoids are employed to press the brake material against the shaft, thereby causing the shafts to stop rotating. Brakes are not needed on the capstan as the two reels will stop, effectively preventing the tape from moving through the pinch-roller-capstan assembly. When the brakes are applied the pinch-roller should be disengaged, and provision is accordingly made to do so. Mechanical brakes of this type will quickly bring the tape to a halt in record or playback, but require somewhat more time to stop the motion in reverse. Of course, if the two brakes are not set to provide more or less equal braking action, there is a possibility that the tape may break (if the supplying reel comes to a screeching halt) or spill over (if the take-up reel stops dead). In order to maintain proper tape tension when stopping, the supply reel should receive somewhat more braking force. Figure 4-6 illustrates a typical brake assembly. When the machine is running, the spring rotates the cam and the brakes are retracted. Actuating the solenoid rotates the cam, forcing the brake lining on to the shaft.

An improved form of brake is shown in Fig. 4-7. Each reel is fitted with a

separate unit. The brake lining is bonded to a thin metallic strap, and the assembly is wrapped around the motor shaft. Usually, a large wheel is placed on the end of the shaft to increase its diameter, substantially. This provides more braking surface. The spring normally holds the lining tightly in place. When power is applied, the solenoid shaft moves out and releases the brake. Turning off the power therefore, applies the brake. Such a system is classed as a "fail-safe" mechanism, for at any time when power to the machine is cut off, the brakes are actuated. Inherently, this system provides greater braking power on the trailing reel, thereby maintaining tape tension.

Another form of braking is the so-called dynamic braking that takes advantage of the electrical circuits of the motors. Rather than apply only mechanical brakes, systems of this nature first reverse the fields of the reel motors, and use the sudden slowing of the motor to aid in stopping the machine. Brake linings and solenoids last much longer when this is used in conjunction with friction type brakes. The machine slows down, also, without snapping tape, as might happen when mechanical brakes are suddenly applied.

As previously mentioned, a reel may contain over 1000 feet of tape, so it is often necessary to run a large amount of tape through the machine before coming to the particular section desired. To permit rapid selection of the desired point on the reel, tape machines are fitted with fast forward modes of operation. Fast forward operation involves much the same mechanisms as fast reverse (or rewind), in that lifters may again be used, and the pinch-roller is disengaged.

Tape transport mechanisms come equipped with one or more motors. Home type machines are usually fitted with a single motor, substantially similar to that found in record changers. The shaft of the motor is linked mechanically to the capstan, and has a heavy flywheel to aid in providing the constant speed required by the tape. Belts are used between the motor and the two reels, and levers either engage or disengage the belts as needed. More expensive machines utilize three motors, one of which operates the capstan, while the other two each drive one reel. The capstan motor in this instance, also has a heavy flywheel, and the motor of the supply reel is operated in the reverse direction at low speed during recording or playback, to provide additional tension on the tape. Although many semiprofessional machines use shaded pole motors, much more accurate timing can be obtained from hysteresis synchronous motors that lock themselves to the line frequency, and stay there. In general, the three-motor machines are not merely higher priced, they are also of higher quality, since each motor has but one job and can perform that well.

As a convenience, home-type machines are usually fitted with a belt-driven "footage" counter. This permits locating specific material at any point on a reel by indicating the amount of tape that has gone through the machine. Another feature of home-type machines is a magic eye, modified vu meter, or neon bulb indicator for checking the recording signal level. Professional machines are usually operated with a vu meter mounted on the amplifier or remote-control panel, rather than on the transport mechanism.

Timing Errors

A fundamental requirement of any recording system is accurate timing, needed to establish the exact bit sequence when reproducing the information. Unfortunately, no means yet exists by which we may obtain perfect timing, for even the best machines contain some small amount of error. If the error is small enough, it need be of no concern, but occasionally timing errors may be large enough to cause trouble.

Timing errors fall into three categories. The most basic of these is lack of proper average speed in the reproducing mechanism, and is most easily thought of in terms of playing a 45-rpm record at either 78 rpm, or 33-1/3 rpm. In either case, the speed is incorrect, and the reproduced signal suffers accordingly. In tape recorders, speed differences of such a vast magnitude practically never occur, but it is possible for a machine that should operate at 15 inches per second, to actually operate at some slightly higher, or lower speed. In general, higher speeds than normal are due to the pinch-roller and capstan not making good contact with the tape, permitting it to slip through. When this occurs, the take-up reel pulls the tape through the machine at a faster than normal rate, giving the same effect as playing a phonograph record just a little too fast. Loose pressure pads may also cause this defect, because the capstan speed is designed to account for the drag of the pressure pad. Bass notes disappear from a system when the speed is excessive, and the sound becomes uncomfortable, since everything is reproduced at a higher than normal frequency. In some instances, it is possible for the slippage to be quite small, in which case the average listener may not be aware of the fact that the system is off time. If a recording is made with a machine that is running too fast or too slow, but then played back at the *same wrong speed*, the error is not noticeable.

Slow speeds are usually caused by additional loading of the mechanical system. For example, if the pressure pads are too tight they may add some extra mechanical drag to the system, causing slow speeds. This has the effect of removing high-frequency components from the signal, and making the result sound rather boomy. A similar condition may be created if the pinch-roller exerts too much pressure on the capstan, again causing mechanical drag. A supply-reel shaft which binds is another cause of slow speeds.

Wow is the name given to the change in pitch when the speed of a recording is suddenly altered. Wows usually occur at the start of a selection, because the machine is brought from standstill to full operating speed in short order. The best correction for wows is to permit adequate warm-up time for the machine, together with a leading groove or length of tape having no signal recorded on it. By the time the recorded section is reached, the machine has stabilized itself. If, however, a sudden drag occurs on the mechanical load of the system, a wow may again be noticed. This often happens with warped phonograph records, due to the speed changing suddenly, once per revolution. Wows are timing errors that occur at low repetition rates.

Although we like to think of our electric motors as constant speed devices, they are almost always varying slightly in speed. A motor that supposedly operates at 300 rpm may be continuously varying back and forth between 299 and 301 rpms. The average rpm is 300, but at any instant the speed may be somewhat different. These minute changes in speed are called *flutter*, and they cause the recorded signal to be constantly changing slightly in pitch. The motors used in most modern tape machines are synchronous motors, that is, they synchronize themselves to the 60-cycle line frequency (which is fairly accurate), and under no-load conditions, remain at speed. Slight variations in load, changes in tape tension, or splices passing through the capstan all cause flutter. Pressure pads may also create severe flutter, and it is this effect that makes them objectionable in professional machines. Flutter tends to add a frequency modulated component to the signal. If excessive, this becomes quite annoying. Two cures exist for flutter, the use of hysteresis motors that hold almost constant speed under varying load conditions, and the addition of a servomechanism to the system to constantly correct for the small errors involved.

Chapter 5

ELECTRONICS OF TAPE RECORDING

Magnetism

Magnetism, and many of its more obvious effects, has been known for many centuries. In fact, one of the earliest books on the subject was published in the 16th century. Only recently, however, has a true knowledge of magnetism been developed, for magnetic effects are closely associated with the structure of the atom.

Electrons spinning in their orbits within an atom, are literally surrounded by forces, some produced by themselves, others by additional electrons and atoms in the immediate vicinity. Interaction of these forces in certain materials causes the spinning electrons to form a magnetic domain. These domains are small volumes of material in which the axes of the spinning electrons are aligned with respect to each other. Each magnetic domain in a given piece of material is always considered to be magnetized to saturation, the maximum possible amount. The resulting magnetic force of the material itself tends to be zero, for the domains are not necessarily aligned with each other, and their individual effects are directed at random. When all the domains in a material are aligned, the overall force appears to lie in the direction of the individual domain alignment. Each domain may be looked upon as an atomic sized magnet surrounded by its own magnetic field.

Whenever a bar magnet (a bar in which the domains are aligned with one another) is suspended freely in air, it tends to line itself up with the earth's magnetic field. The end of the bar pointing north is called the "north-seeking" or "north" pole of the magnet, while the other end is the "south" pole. The force of attraction or repulsion commonly associated with magnets is concentrated at the poles, and is directed along specific paths known as *flux lines*

(Fig. 5-1A). By long standing custom, flux lines are assumed to emerge from the north pole of the magnet and to re-enter it at the south pole. There are exactly the same number of flux lines radiating from the north pole as there are returning to the south pole, for each flux line is actually a closed loop representing the direction of domain alignment in the magnet. Inasmuch as the domains point in the same direction within the magnet, the flux line connects together the ends of those domains appearing in a straight line. Inside the magnet the line is continuous, and moves from the south pole towards the north. Outside,

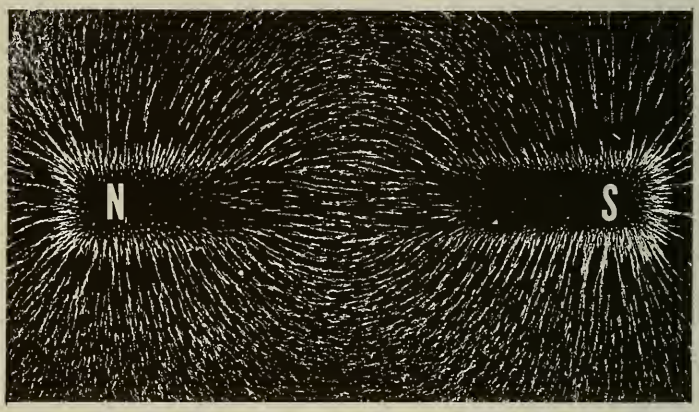


Fig. 5-1A. Bar magnet showing flux lines produced with iron filings.

of course, the lines bend around away from the north pole, and travel through the air to the south pole, as illustrated in Fig. 5-1B. The collection of flux lines external to the poles is referred to as a magnetic field or a flux field.

Magnets generally fall into two categories, permanent and temporary, the distinction being based on the action of the domains. An external force is required to align the domains in a magnetic material. If, after the aligning or magnetizing force is removed, the alignment remains unchanged for a long period of time, the material is classed as a permanent magnet. On the other hand, if the alignment disintegrates when the force is removed, the material is a temporary magnet. Both types are important in tape recording, for the tape itself is a form of weak permanent magnet, while the heads are temporary magnets.

Domains in a magnetic material may be aligned electrically or mechanically. In any event, the alignment creates flux lines that are closed loops. The complete path taken by the lines is called a *magnetic circuit*. In this circuit the number of lines, or *total flux*, is analogous to the current in an electric circuit. Effectively, the force that causes the alignment also creates the flux. It is therefore the magnetic equivalent of voltage, and is known as the *magnetomotive* force, or *mmf*, of the circuit. Due to the close association between magnetism and electricity,

mmf is measured in units called ampere-turns. Still another analogy remains, for in the magnetic circuit there is opposition to the passage of flux lines. This opposition is termed *reluctance*, and is the analog of electrical resistance. Flux passing through a reluctance produces an mmf drop, in the same way as current passing through a resistor provides a voltage drop. The analogies between electrical and magnetic circuits go even further, for magnetic circuits obey both Ohm's law and Kirchhoff's law.

Reluctance in a magnetic circuit depends, among other things, upon the material used. Most magnetic materials have relatively low reluctances, with the man-made alloys such as permalloy, exhibiting values even lower than iron. Conversely, air and other nonmagnetic materials have very high reluctances. As with resistance, reluctance increases with the length of the path, and decreases as the cross-section area increases.

Flux lines in a magnetic circuit repel each other. In fact, it is this repulsion that causes the lines to bend away sharply at the poles of a magnet. Moreover, flux lines tend to follow the path offering the least reluctance. In a bar of magnetic material then, the flux is confined inside the bar for its entire length, emerging only at the poles. Within the bar, too, the repulsion between the lines

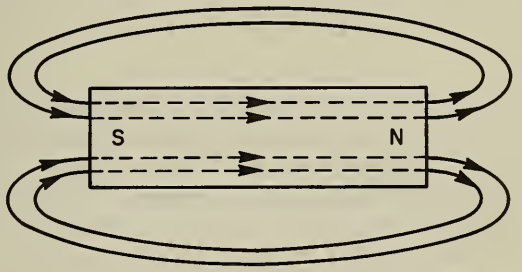


Fig. 5-1B. Pictorial representation of flux lines in a magnet.

produces an even distribution of flux throughout the cross-section area. The amount of flux per unit of cross-section area in a magnetic circuit is referred to as the *flux density*, and it is calculated by dividing the total flux by the area. For example, if 100 lines exist in a cross-section area of 0.01 square inch, the flux density is 10,000 lines per square inch. In magnetic circuits, flux density is a much more useful quantity than the total flux.

Another useful unit is the *magnetic potential gradient* (sometimes called field strength). Actually, this is the mmf per unit length of the circuit, and is found by dividing the physical length of the circuit into the mmf. To illustrate, an mmf of 100 ampere-turns appearing across a path 10 inches long, produces a gradient of 10 ampere-turns per inch.

Suppose we had a piece of material in which the magnetic potential gradient

could be increased or decreased at will. What would happen? It seems clear that any such increase would tend to increase also the total flux radiating from the material. Since the cross-section area of the material does not change, the flux density must increase. Plotting the relationship between these two quantities produces the *BH* curve shown in Fig. 5-2. Note that at some point on the curve

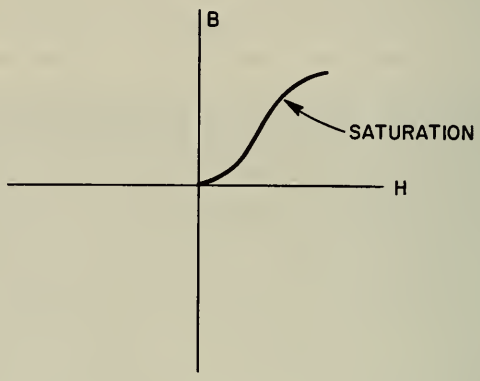


Fig. 5-2. Typical *B-H* curve.

large increases in H (the potential gradient) cause practically no further increases in B (flux density). This is called the saturation point of the curve. Now, suppose that after the saturation point is reached we *reduce* the value of H to zero. B does not return to zero, but rather to some positive value. If H is now increased in the *negative* direction, B will eventually reach zero. Continuing to increase H in the negative region we obtain another saturation point, but now both B and H are negative. Reversing H again, and increasing it to a positive value, once more causes B to return to a positive value, but not quite the same as the first time. After several successive reversals of the value of H, the pattern repeats itself over and over, and traces out the closed loop shown in Fig. 5-3. This is known as a *hysteresis* loop, and the enclosed area of the loop represents the energy utilized in aligning the domains of the material.

Tape Heads

When tape is passed from the supply reel to the take-up reel on a transport mechanism, it passes over a series of heads whose function it is to remove previous signals from the tape, record a new signal, and then play it back through another amplifier channel (unless the machine has only two heads, in which case no simultaneous playback is possible). These heads are the heart of the tape machine, and for good results, must be of high quality. All heads are similar, whether they are used for erase purposes or recording, or whether they

are to be incorporated into home-type or professional machines. Small differences appear between erase and record heads, and of course, high-quality heads reflect better construction.

Figure 5-4 illustrates a typical head. A coil of wire, somewhat similar to that of an earphone, is wrapped around an iron core, and the entire assembly is then placed in a metal shield. The core is brought around to the front and formed into pole pieces to provide a continuous metallic path, except for a small space at the front center. This space, or *gap*, is important, for the signal to be recorded appears here in the form of flux lines across the gap. The core and gap form a complete magnetic circuit. Although some gaps are merely empty space (and consequently filled with air) others are often filled with physical "spacers" to maintain exact dimensions. The dimensions of the gap determine the amount of current required by the head to lay down a good signal on the tape, and conversely, the amount of signal obtainable from the tape in playback. The shorter the gap, the more difficult it becomes to obtain adequate signal strength, for flux lines tend to jump straight across short gaps. In playback, the gap width affects the frequency response. In practical heads a compromise must be made between high-frequency response and signal amplitude.

The gaps placed in recording and playback heads should be fairly deep. Fundamentally, this is done to prevent deterioration of the head due to the

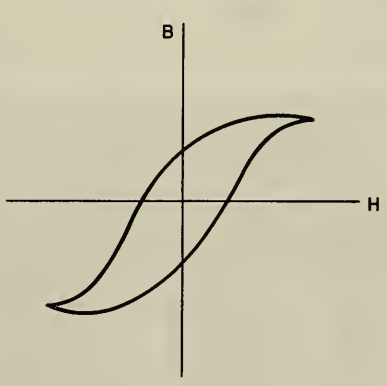


Fig. 5-3. Typical hysteresis loop.

abrasive action of the tape on the pole pieces. Excessive wear in a head will cause the gap to become longer unless it has been built with deep straight sides. There are many ways in which deep gaps can be manufactured, but the use of laminated pole pieces and cores, is probably the easiest. The simplest, and most apt to wear head, is made by butting two pole pieces together, and then bonding them to a common nonmagnetic backing to supply structural support. This type of gap is usually supplied with home-type machines, and to facilitate servic-

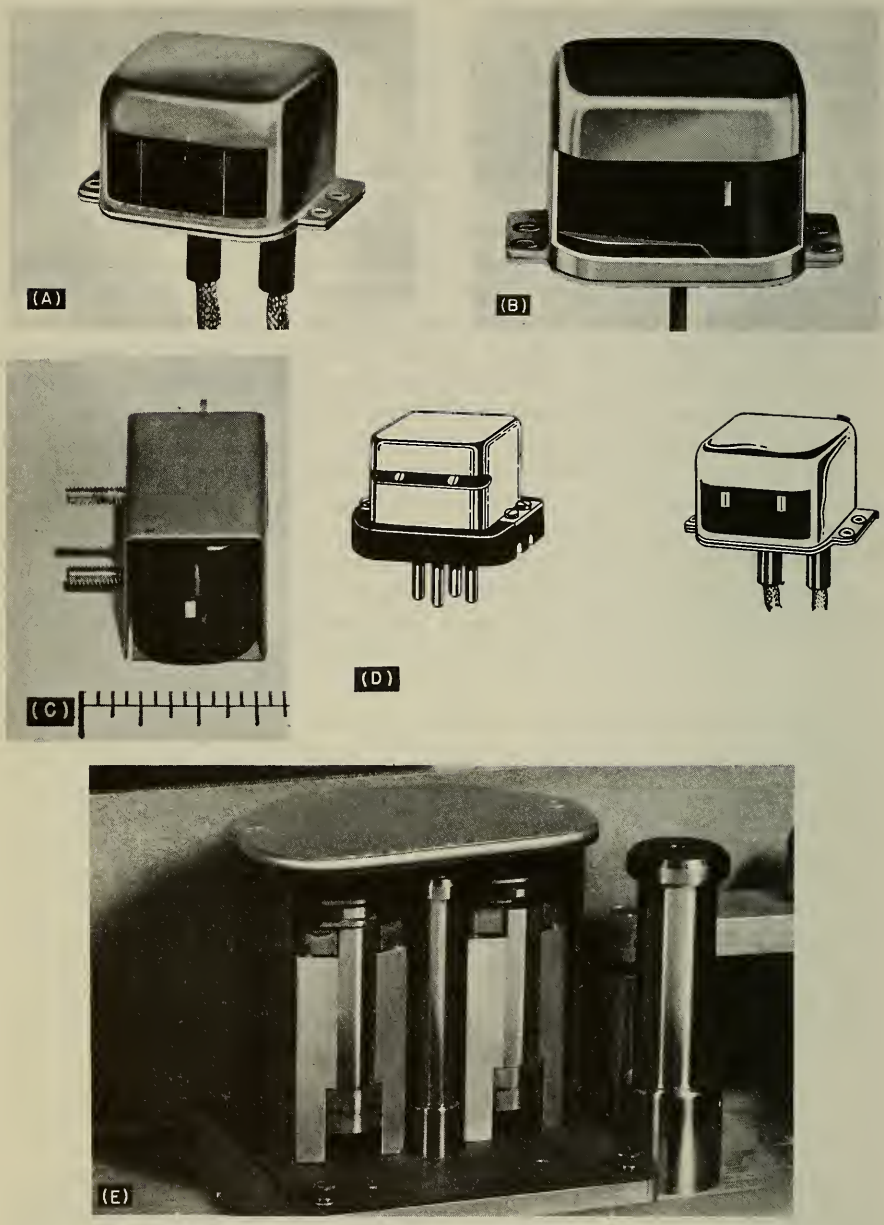


Fig. 5-4. (A) — (D) typical heads; (E) audio- and cue-track multiple heads from the Ampex VIDEOTAPE recorder. The head to the left erases top and bottom edges of the 2-inch wide tape. The right head is a combination record-playback unit; audio is at the top, cue at the bottom. *Courtesy: (A) through (D) Shure Brothers, Inc., (E) Ampex Corp.*

ing, the pole pieces are made removable. Two such head units on one machine may have entirely different frequency response characteristics, simply because the edges of the pole pieces are not carefully machined, causing the gaps to differ substantially in length.

Figure 5-4 also indicates gap terminology and dimensions. The depth is the measurement through a cross-section of the gap, as shown. Unfortunately, width and length have often been confused in tape gaps. The length should be considered as the distance through which the flux lines travel, but popular termi-

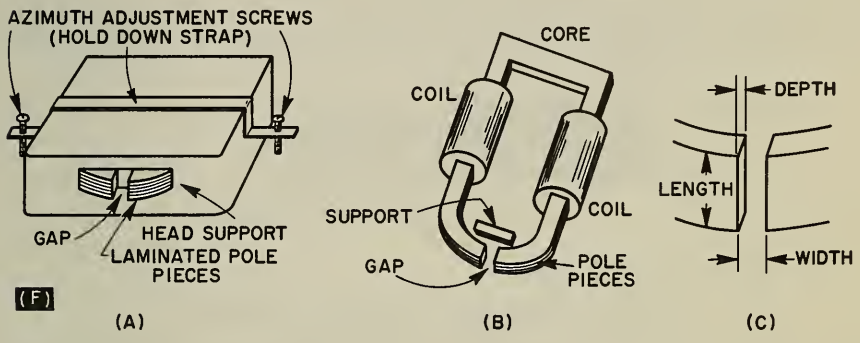


Fig. 5-4. (F): Diagram of (A) recorder head; (B) interior view; (C) gap dimensions.

nology has made this the *width*. The length is therefore the dimension of the pole piece at a right angle to the flux lines.

Consider now a typical recording head. As was seen previously, this is composed of a set of coils through which the core material is passed. If a current is sent through the coils, a magnetomotive force appears in the core. This tends to send flux lines around the closed magnetic path formed by the core. However, in their journey around the core the flux lines encounter the gap, which has a reluctance very much greater than the core material itself. When no tape is present, the flux lines are forced to jump across the gap. In a complete metallic magnetic path, all the flux lines are confined to the dimensions of the core, since it offers the path of least reluctance. At the gap this is no longer true, so the flux lines bend away from each other, producing a fringing field that protrudes from the surface of the head as indicated in Fig. 5-5. Now, if a piece of tape is placed in contact with the head (at the gap), flux lines approaching the gap see in the tape a path of much lower reluctance than that provided by the gap itself. They therefore pass from the pole piece into the tape, travel down the tape to the vicinity of the opposite pole piece, and then return to the core at that point.

Flux passing through the tape applies a force to the domains in the oxide coating, causing them to align their positions according to the amount and direc-

tion of the flux (Fig. 5-6). As the tape moves past the head, the domain orientation established by a flux line remains on the tape because the line has no further effect once the tape has passed the gap. The pattern is locked in the tape by this orientation of the domains, and remains there until another set of flux lines is applied to the tape, in which case the domain pattern changes.

To play back a signal, the tape is passed over another head similar in construction to the recording head (Fig. 5-7). In fact, it may even be the same unit. In this instance, however, no current is fed to the coil, as it is connected to the input of an amplifier. As the tape with its magnetic pattern passes across the gap of the head, the flux lines radiating out of the domains of the tape enter the iron core, since it offers a lower reluctance path than the surrounding

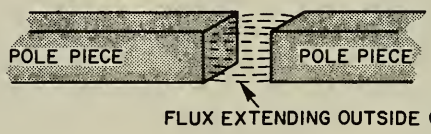


Fig. 5-5. Production of a fringe field across a gap.

air. The flux lines passing through the core vary, depending upon the amount and direction of the flux on the tape, and in turn, these varying fluxes induce currents in the coil surrounding the core. The current, varying now in conformity with the tape signal, causes a voltage to appear across the terminals of the coil, and it is this voltage that is coupled to the amplifier input.

An important consideration in gaps is the effect of the gap on frequency response. Generally speaking, the high-frequency response of a tape recording depends upon three factors, the speed of the tape past the heads, the width of the playback gap, and the machining of the record gap. As an example, suppose that in playback the tape is moving past the heads at 15 inches per second, and contains a 15 kc note. A full cycle of such a note occupies 1/1000 of an inch on the tape. However, remember that a cycle is composed of both positive and negative half cycles, each of which takes up 5/10,000 of an inch. If both positive and negative half cycles appear across the gap simultaneously, the effect of one cancels the other, resulting in zero output. (Oddly enough, this effect does not appear in the record head gap. Tape passing a recording head gap "remembers" only the last impression it receives on *leaving* the gap. It is the straightness of the trailing edge of the recording gap that determines the highest recordable frequency.) In order to play back this signal at the speed indicated, then, a gap no greater in width than a half cycle is needed, in this case 5/10,000 of an inch. On the other hand, if the 15 kc signal were recorded at a tape speed of 30 inches per second, a gap width of 1/1000 of an inch would be adequate. For slower speeds the playback gap width must be shortened to provide adequate high-frequency response.

In phonograph disc recording, a very important adjustment is the angle the cutting needle makes with the surface of the disc being recorded. In a tape recorder, a like condition exists. It is essential to have the gap of the heads lined up perpendicular to the tape itself as it passes across the head. Should the gap present any angle other than 90° to the tape, a loss in high frequencies results, as the gap then appears to the tape to be wider than it is in reality. For

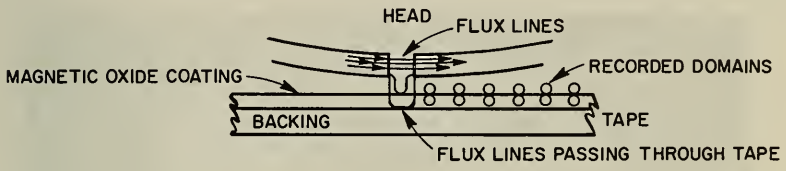


Fig. 5-6. The recording process.

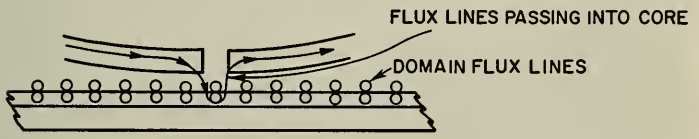


Fig. 5-7. The playback process.

this reason, heads are usually mounted together with some sort of screw arrangement that permits making adjustments. It is clear that all the heads must be so aligned, for if only the recording head is properly set, we may record any signals we wish, but the playback head will not pick them up. Test tapes that have been recorded on machines with perfectly adjusted heads are available for checking head alignment. Maximum output is obtained from these tapes when the head is properly adjusted.

Erase heads are somewhat different from record or playback heads in that they usually operate with a constant-amplitude, high-frequency a-c signal. To be sure of good erasure of past recordings, it is customary to supply a large current to the erase head, thus overriding any recorded peaks. The gap width of an erase head is much wider than in a recording head, and with an a-c erase signal this allows the flux field to reverse itself many times as the tape passes the gap. Since the flux re-enters the pole piece at the end of the gap, the result is that the tape sees first an increasing then a diminishing alternating field as it goes past the erase head, and comes out not quite completely demagnetized.

Erasure can also be made with permanent magnets. These are retracted from the tape during playback. Permanent magnet erasure is not as satisfactory as a-c erase since the tape is definitely magnetized in one direction by such a device.

Bulk erasers are also available. With these devices an entire reel of tape is demagnetized at one time by rotating the reel in a very strong 60-cycle field (Fig. 5-8). Bulk erasure is usually more thorough than that provided by a recorder's erase system.

We must also consider the effect of the hysteresis loop in the magnetic recording system. The magnetomotive force that causes flux lines to travel

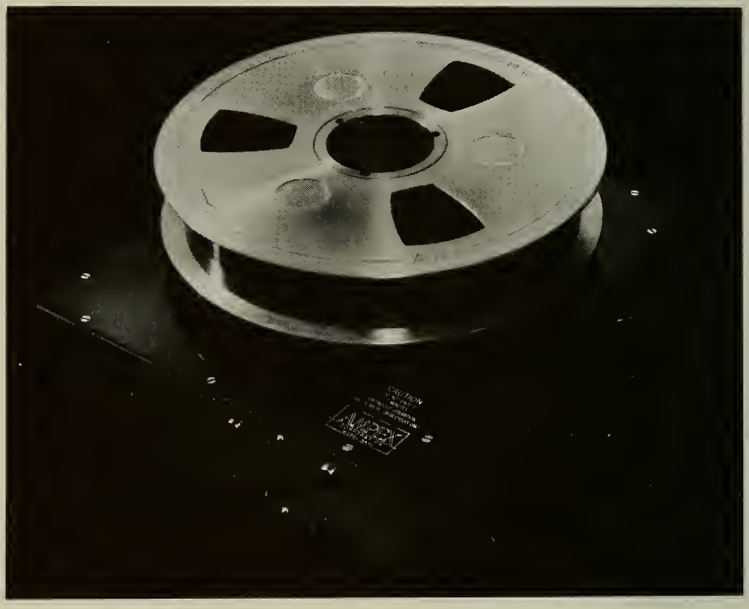


Fig. 5-8. Typical bulk eraser. *Courtesy Ampex Corp.*

around the core of the recording head is produced by the coil current. This mmf is directly proportional to the current in the coils. In turn, the flux is directly proportional to the mmf applied to the system, and further, the flux density, B, is directly proportional to the flux. Now, a graphical plot of two factors directly proportional to each other results in a straight line. We would like the recorded magnetic signal on the tape to be directly proportional to the current, so that a linear transfer characteristic exists between them. A glance at the hysteresis curve shows that this cannot be done since H, which represents the magnetizing force applied to the tape, does not have a straight line relationship with B. It therefore becomes necessary to make certain changes that will cause the hysteresis loop to collapse, or shrink into a line. H will then be directly proportional to B, which in turn is directly proportional to the flux, and so on until we arrive back at the current in the coils.

Suppose an a-c signal is applied to an electromagnetic system. The periodic reversals of current will cause H to alternate, creating a hysteresis loop similar to that shown in Fig. 5-3. Suppose now, that we reduce the amplitude of the signal. This should produce a smaller loop. After this has been done, let us reduce the amplitude further, resulting in a still smaller loop as in Fig. 5-9. If this is continued until the signal is zero, a family of loops is obtained. The ends of each loop may be connected together with a line to obtain a B-H transfer characteristic. This is shown by the dotted line in the figure, which is almost,

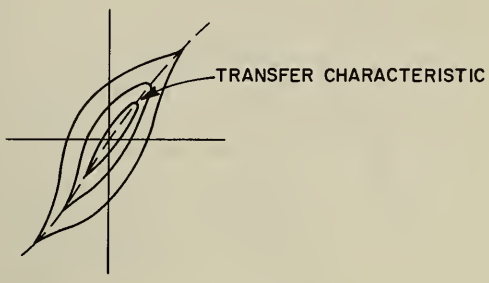


Fig. 5-9. Development of the B-H transfer curve.

but not quite, a straight line. Since this represents the relationship between B and H for varying amplitude signals, it may be used as a transfer characteristic provided the necessary precautions required to stay on the straight segments, are taken.

Essentially, a recording head requires current through its coil to develop flux across the gap, but most signal sources (microphones, phonographs, TV cameras, etc.,) are low-level devices, and the amount of current available from them is vanishingly small. Attempting to record such signals directly, would result in excessive noise and poor fidelity. What is more, the gap flux is produced by the mmf, which in turn, is the product of the coil current times the number of turns on the coil. Thus, to obtain an adequate mmf for recording purposes, low current sources necessitate large coils with many turns. Conversely, a small coil with fewer turns, and therefore more practical, could be used if the signal current were to be increased. Clearly, this calls for the use of an amplifier to raise the signal to an appropriate level. However, it is important to note that excessive current is just as bad as none at all, for if the head current is too large, the recording signal will saturate the tape, creating distortion. In general, tape recording amplifiers contain several stages; one, or more, depending upon the source, to boost the signal level, perhaps another for equalization (see below), and a final stage to deliver the signal to the head in the form of a sufficiently high current to produce a good recording.

Tape playback systems also require amplifiers. The voltage developed across

a typical playback coil is comparable in amplitude to the voltage available from a crystal microphone. If this were fed into a standard audio system, the output from the loudspeaker would be quite low, since the voltage developed by the head is insufficient to drive the 1st stage of the amplifier. For this reason, tape playback signals are first sent through a *preamplifier* whose purpose is to increase the level prior to the main amplifier stages. To reduce noise and hum, preamplifiers are usually located as close to the head as is practical. Audio recorders

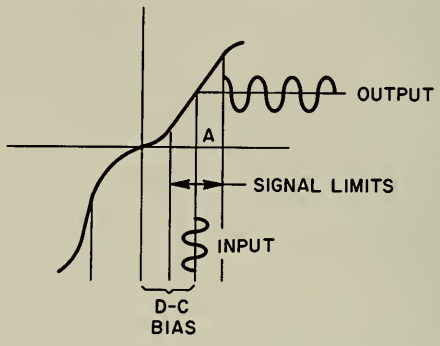


Fig. 5-10. The effect of d-c biasing.

that are not equipped with loudspeakers and regular amplifiers, utilize the preamplifier to develop an output signal of approximately 1 volt, which may then be fed by cable into an audio amplifier in the same manner as a phonograph.

Recording Head Bias

Figure 5-10 shows the *B-H* transfer characteristic in a somewhat exaggerated form, used to simplify explanations. In order to obtain linear transfer, the signal must be restricted to the straight line portions of the curve. Suppose some dc is added to the recording signal. The signal itself, being alternating, merely adds to or subtracts from this d-c component. If the amount of dc added is sufficient to shift the center axis of the input signal to point *A*, the operation is on a straight line segment of the curve. Bias, then, is merely a component added to the system to make it operate at a given point on the transfer curve. In this case, use of the d-c bias means that the signal has to be limited so that its peaks do not extend into the curved region. Low-amplitude signals are then recorded, and the result will probably have a high signal-noise ratio. On the other hand, if a large amount of an ultrasonic component is used as a bias, the mixing of this with the recording signal produces a composite signal as shown in Fig. 5-11.

Waveform *X* in the diagram represents the signal to be recorded. Waveform

Y is the ultrasonic bias. Adding (not modulating) the two gives waveform *Z*. This is applied to the *B-H* transfer curve along the *B* axis. Note that the variations in the input envelope now fall onto the straight segments of the transfer characteristic. Each straight line segment provides a separate output, but the two are in phase. The signal recorded on the tape is therefore the sum of the two waveforms indicated. This, of course, is larger than the output obtained with d-c bias. Further, the ultrasonic signal is reduced substantially by

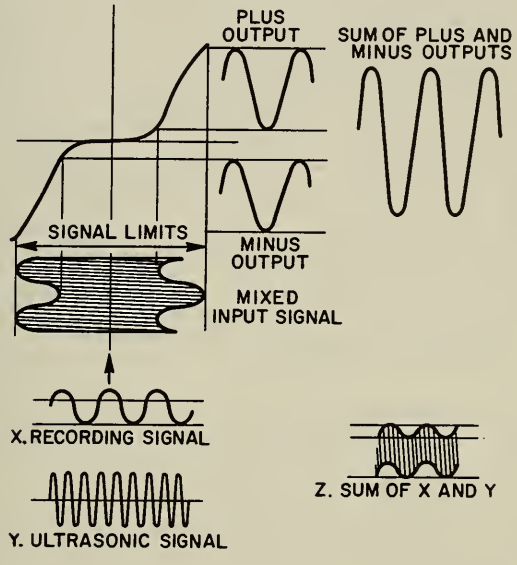


Fig. 5-11. The effect of ultrasonic biasing.

the curve, and what is left is at too high a frequency to be recorded. Generally, the ultrasonic bias is at least 5 times the highest frequency to be recorded, and is also about 10 times higher than the recording signal in amplitude.

Equalization

To be worthwhile, any recording system should be able to reproduce all the recorded signals without introducing any changes. Thus, if two signals, one high-frequency and one low-frequency, one at a high amplitude, the other only half the amplitude of the first, are recorded, the playback should produce the same two frequencies at the same relative amplitudes. Suppose that the high-frequency signal is the lower amplitude component. In reproduction, if the amplitude of this signal is less than one half that of the other, we say that the system has poor high-frequency response, since it has obviously reduced the

amplitude of the high-frequency signal to a lower value than it should have been. On the other hand, flat frequency response indicates that all frequencies within the spectrum being handled are given the same treatment. Amplifiers represent no problem in audio tape recording, but both the tape and the heads cause trouble. As indicated previously, tape speeds and gap lengths both affect the high-frequency response of a tape system, as does stray capacity in the coil.

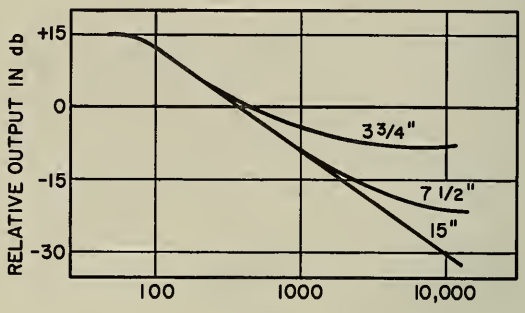


Fig. 5-12. A typical tape-equalization curve.

Additionally, the core material of the heads may also be a troublemaker, since hysteresis losses occur here, and these tend to increase with frequency.

All in all then, at any given speed, it is possible that the overall frequency response of a tape system may not be sufficiently flat. It is the purpose of an equalizer to make it so. The equalizer inserts reactive components that alter the existing frequency response, and provide the desired result. Equalizers can be built to boost or attenuate either the low, high, or middle range of frequencies, and are designed to complement the system with which they operate.

In equalizing a recording system, two choices are available. Either we equalize the system before making the recording (pre-equalization), thereby taking into account everything that will later contribute to poor response, or we equalize during playback (post-equalization), correcting for the previous defects. In the former process, the equalizer is inserted into the circuit in the recording amplifier, and it affects the currents being applied to the recording head. In the latter arrangement, the recording is made with no attempt at correction; all the correction is then placed in the playback amplifier. A combination system in which some correction is made in the recording circuits and the balance in playback, may also be used. This combination approach is often useful, for if it is found that high-frequency noise is getting into the recording from the tape, it is possible to boost the high-frequency response during recording, and then cut it down during playback. The overall system is then flat, but the noise has been lowered by a considerable degree.

The curve shown in Fig. 5-12 is typical of playback equalization. Output from

a magnetic recording during playback is directly proportional to frequency, simply because the voltage developed across the playback head depends upon the *rate of change* of flux passing the gap. Higher frequencies, of course, represent higher rate of change, and as the frequency increases, so does the output. The increase is at a rate of *6 db per octave*, which merely means that doubling the frequency also doubles the output voltage. Clearly, this rising characteristic must be eliminated if faithful reproduction is desired. However, to provide adequate high-frequency response, it is often necessary to boost the overall recording-playback characteristic somewhat, as the frequency edges up. Thus, in the curve shown, the output is reduced by a rate of 6-db per octave up to a predetermined point, at which the curve shelves off. This flattening of the curve at the shelf point indicates that no further decrease in output is provided by the equalizer circuit, and the 6 db rise per octave due to the playback head now boosts the response, effectively raising the output at the higher frequencies.

The frequency at which the shelving occurs depends upon the speed, as well as other characteristics of the system being equalized. However, note that the 7½-inch speed shelve is at a lower amplitude than that for the 3¾-inch speed, indicating that the boost starts at lower frequencies for the slower speed. Most tape recorders use an additional switch section on the speed-change switch to insert the equalizer circuits, since the equalization required depends upon the speed of the tape.

Tape Characteristics

Modern magnetic recordings are made on flexible, durable, plastic tape, coated on one side with a finely pulverized magnetic material. The coating itself is made of red ferric oxide, specially treated to provide the magnetic qualities desired in the finished tape. The oxide, after being pulverized, is mixed with a binder, and then tumbled together with steel balls for a substantial period of time. This ensures thorough mixing of the binder and oxide. When the tumbling process has been completed, the mixture is filtered to remove the larger clumps of material, since only the smallest particles are desired for tape coating. After filtering, the oxide-binder mixture is applied to the tape backing in special machines that automatically check the coating thickness, and eventually wind the tape onto spools. During this process, the coating is applied in liquid form. While it is still wet, the coated tape is passed through a magnetic field that aligns all the particles, which are needle shaped, so that their longest dimension parallels the length of the tape. Orienting the particles in this manner provides a better recording characteristic, and improves the signal-to-noise ratio as compared to nonoriented tape. After orientation, the coating is dried, locking the particles in the aligned pattern.

Before spooling, the coating must be made as smooth as possible, so the tape is sent through a polishing system composed of a stiff, high-speed brush, followed by a buffing wheel. After buffing, the tape is folded back upon itself so

that the coated surfaces of the two sections rub against each other, giving a final polish to the tape. The hardness of the coating when processing has been completed is important, for if the tape is too soft, the coating will rub off and clog the head gaps. Conversely, if the coating is too brittle, the heads may chip pieces off the tape.

The effect of particle size on recording quality can not be overemphasized. Mixtures of large and small oxide particles make it difficult to obtain a smooth

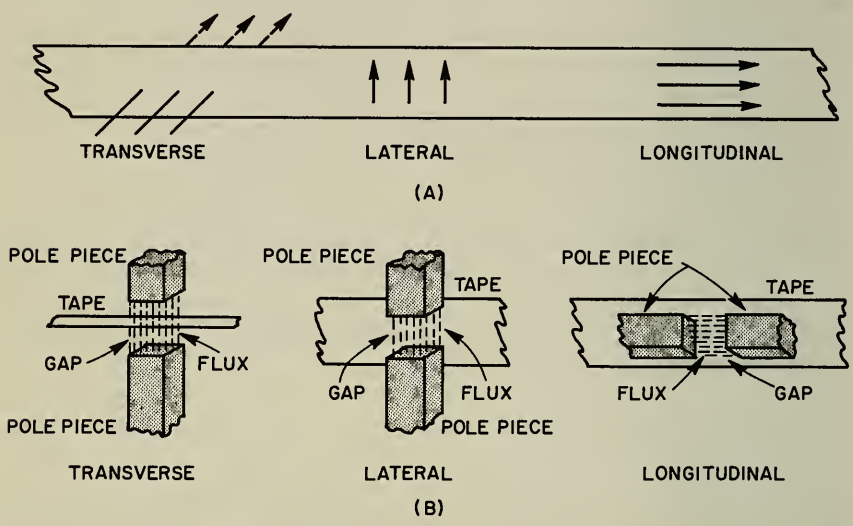


Fig. 5-13. (A) Magnetization directions for tape recording. (B) Gap geometry for various polarizations.

polished coating, and furthermore, they increase the noise level of the tape. Even worse is the effect of large particles on frequency response, as the following example shows. Suppose a 15-kc signal is to be recorded on a piece of tape driven past the recording head at 15 inches per second. The wavelength of one cycle of this signal on the tape will be 1/1000 of an inch. It is necessary, however, to provide for the recording of the half cycles, each of which occupies only 5/10,000 of an inch. As a practical matter, if a reasonably accurate recording is to be made, at least 10 oxide particles must be included per half cycle. This in turn, means that each particle must be a maximum of not more than 5/100,000 of an inch in diameter in order to record the signal. For higher frequencies the particles have to be even smaller. Standard tapes are manufactured with particles approximately 1 micron long and 0.2 micron wide.

Plastic backings used for magnetic tape may be of several thicknesses, ranging up to approximately 2 mils, depending upon the tensile strength of the plastic, and the desired playing time per reel. In general, thinner tapes are made of

Mylar, since it has a much greater tensile strength than other commonly used plastics. The backing itself must be smooth before the oxide coating is added. A uniform coating thickness is essential, and this is possible only when the oxide is placed on a smooth surface, one containing no peaks or troughs. The finished product, backing with oxide coating, is made in several standard thicknesses. usually given as 1 mil, 1½ mils, and 2 mils, although the actual thicknesses are slightly larger due to the coating.

Magnetic signals may be recorded on tape in three directions, each at right angles to one another. These are shown in Fig. 5-13. When the direction of the magnetic field lies along the longest dimension of the tape (usually the same direction as the tape motion), we say that we are using *longitudinal* magnetization. When the field is at right angles to the direction of tape motion, the tape is said to be *transversely* magnetized, and if the field is applied through the tape, the term *perpendicular* magnetization should be used. Audio recorders use longitudinal magnetization, but television tape recorders use a modified form of transverse (although it is often referred to as lateral) magnetization to be discussed in a later Chapter.

Magnetic tape is available in several widths. For audio recordings, the tape is ¼-inch wide, and may contain as many as four separately recorded tracks parallel to each other. When multitrack recordings are made, it is customary to provide a guard band, or space, between tracks, to prevent interference. This is similar to the space between grooves on a disc recording, and serves to isolate one track from the other. For dual-track systems on ¼-inch tape, a guard band of approximately 25 mils is used. Other applications may require the use of ½-inch, or 1-inch wide tape, containing many tracks, together with guard bands. Wide tape permits more information to be recorded on a given reel size.

When virgin tape is permitted to pass a playback head, a hissing noise results. In practice, the level of the hiss is about 60 db below the saturation level of the tape, so if a recording is made at a sufficiently high level, the noise becomes unnoticeable, although it is still present. In multitrack systems, if a recorded track does not completely cover the playback head gap, the noise level of the guard band adds to the track noise level, reducing the overall signal-to-noise ratio. When a signal track slips off the playback gap so that ⅓ of the gap length is covered by a guard band, the noise level increases by 3 db. If track and guard band each cover half the playback gap, the noise level increases by 6 db. A shift of only ⅛ of the gap length off the track adds 1 db to the noise level, and in critical applications, even this may be annoying. Multitrack systems therefore require much more exacting lateral alignment of the heads than do single-track systems.

Head design for multitrack systems also presents difficulties. Inasmuch as playback is accomplished by causing flux to enter the core of the head, there is a distinct possibility that stray flux lines from one track may enter the wrong core, producing an erroneous signal in that core. Undesired signals from adjacent channels are referred to as *crosstalk*, in order to differentiate them from other

noises that might be present. In any given channel the presence of crosstalk decreases the signal-to-noise ratio, as it is an unwanted component. If the crosstalk level is equal to the noise level, the overall signal-to-noise ratio decreases by 6 db. In the unlikely event the crosstalk exceeds the normal noise level by any

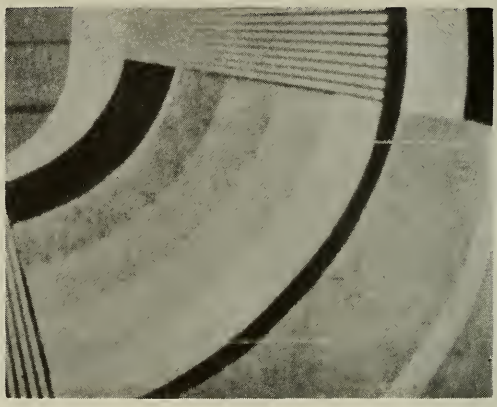


Fig. 5-14A. Drop-outs caused by tape imperfections in a reproduced video recording. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

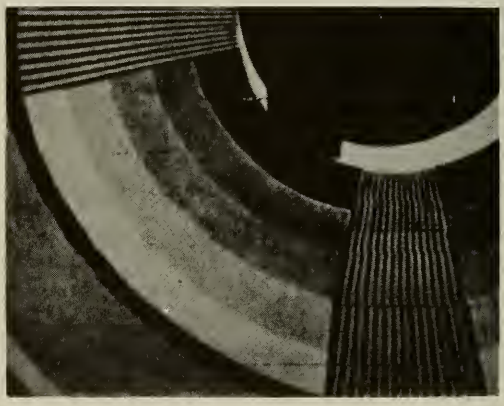


Fig. 5-14B. The effect of scratches in the tape coating. Physical scratches in the magnetic material cause noise flashes that form a geometrical pattern, usually diagonal. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

large amount, it is the crosstalk alone that determines the signal-to-noise ratio. In multitrack systems, crosstalk should be held to a minimum.

Tape used for recording video signals has to meet much more stringent requirements than that used for audio applications. In addition to being mirror-smooth, scratches, dust, creases and dents have to be completely eliminated, for if they are present on the tape, drop-outs occur. A drop-out is a momentary loss of signal during playback, and may cause dots or flashes, white, gray, or black, to appear on the screen. Figure 5-14A shows the effect of drop-outs in a reproduced picture. The magnitude of the drop-out problem may be judged by considering that a reel of video tape has an area as large as a tennis court, while the imperfections being looked for are many times smaller than a grain of sand. For video applications, also, the oxide particles are oriented transversely rather than longitudinally, as is done for audio tape. This results in a 6-db improvement in the signal-to-noise ratio for the transversely recorded video signals. Figure 5-14B shows the effect of scratches on tape.

Print-Through

One defect of the magnetic recording system that has not yet been completely overcome, is the tendency for the domains in a given section of tape to influence those in another section. Primarily, this difficulty is caused by the fact that tape is stored on reels in which one layer of tape is wound directly over the next. If a strong signal has been recorded on a particular segment of tape, the flux radiating from the domains of this segment may be strong enough to penetrate through 1 or 2 mils of plastic backing. When this occurs, the radiating flux lines see in the adjacent tape layer a low reluctance path, so they take it, imprinting a false signal at this point on the tape. In replaying such a tape a faint echo of the original strong signal appears, and cannot be eliminated. For obvious reasons, this is called "print-through". One method of reducing print-through is to use a thicker base. As this is not feasible, tape manufacturers are attempting to develop methods by which print-through may be either reduced or eliminated.

Chapter 6

VIDEO RECORDING

Video Recording Problems

Recording a video signal on tape poses problems, for the video bandwidth exceeds by far that which a standard audio tape machine is capable of handling. Furthermore, the high frequencies involved in video, 4.5 mc, make recording even more difficult, for in order to record such frequencies the tape speed and the gap must both be drastically altered. Early attempts at recording video information were hampered by practical difficulties, and only a makeshift solution was arrived at. In these attempts, the video signal was split into 4 parts, each 1-mc wide, producing bands of 0-1 mc, 1-2 mc, 2-3 mc, and 3-4 mc. The last three bands were heterodyned down into the region of from 0-1 mc, so that 4 equal frequency bands were available. Each was then recorded on a separate track. In playback, the heterodyne principle was again used to restore the three converted bands to their proper frequencies, after which the bands were combined into a composite signal. Unfortunately, the tape speed needed was rather high, and large reels, 20 inches or more in diameter, were necessary for recording a 15 minute program. A system substantially similar to this was at one time in use by the BBC (British Broadcasting Corporation) in England, recording the video signals on ½-inch wide tape. The British television system, it should be noted, provides less resolution than the American system.

The fundamental difficulty in recording wideband signals on tape is due to the tape and the playback head, which together limit the band of frequencies that can be recorded. Playback heads, as noted in Chapter 5, produce an output that rises 6 db for each octave increase in frequency, simply because the head output is proportional to the *rate of change* of the flux on the tape. Thus, if an adequate signal exists at some high freqeuncy, as the frequency is reduced the

output falls off. In other words, good high-frequency response is accompanied by poor low-frequency response. To illustrate, suppose we play back a test tape with signals ranging from 20 cycles to 20 kc. Suppose also, that at 20 kc the signal is good and strong. Then at 10 kc, the output is 6 db less, because the frequency has *dropped* an octave. At 5 kc another 6 db-drop appears, and this continues until finally, at 20 cycles, the output is 60 db less than it was at 20 kc. The 60-db reduction is as far as we can go, for at this point tape noise becomes excessive and blanks out the signal. The important point is, that regardless of the upper frequency selected, today's magnetic tape-recording systems can handle only a range of approximately 10 octaves.

Let us now consider the video signal, which extends from 30 cycles (neglecting the d-c component) to upwards of 4 mc — a spread of more than 18 octaves. To fit this wide band into a spread of 10 octaves or less, both the Ampex and RCA machines translate the video information into a vestigial sideband (a signal with part of one sideband deliberately removed) f-m signal extending roughly from 1 to 7 mc, thereby reducing the band to several octaves. In addition, using f-m permits recording all the signal near the saturation level of the tape. This improves the system's signal-to-noise ratio. The f-m signal used here is rather unusual, and will be discussed in more detail in Chapter 8.

The width of the gap in a playback head limits high frequencies. When the physical length of 1 cycle on the tape equals the gap width, currents induced in the head by the positive and negative half-cycles of the recorded signal cancel each other, resulting in zero output. But the physical wavelength of a signal on the tape is determined by both the frequency of the signal and the speed with which the tape passes the head.

At 15 ips, a 15-kc signal occupies 0.001 inch of tape per cycle. To reproduce this signal, a maximum gap width of 500 microinches may be used. Now, if the upper-frequency limit is to be extended beyond 15 or 20 kc, it becomes necessary to either increase the tape speed so that each cycle occupies more space along the tape, or decrease the gap width, or perhaps both.

Suppose we reduce the gap width to 100 microinches, which is about the smallest practical size that can be manufactured. This extends the high-frequency response out to 75 kc. But we want to record frequencies much higher than this. Some simple arithmetic shows that if the tape speed is increased 100 times, to 1500 ips, it would be possible to record up to 7.5 mc. Pulling tape past a recording head at this speed (which is equivalent to 90 mph) means that about 450, 000 feet of tape would be needed for a 1-hour program.

Fortunately, it is not necessary that the tape itself move at this tremendous velocity, for it is the *relative* velocity between tape and head that does the work. This being so, a further improvement is afforded by moving the head as well as the tape. The only practical method of accomplishing this is to rotate the head transversely across the tape, while the tape is pulled slowly from one reel to another. To provide still better results, 4 heads are used on a rotating head wheel, so that each head comes into contact with the tape as the previous head

leaves. Rotating the head wheel at 14,400 rpm permits pulling tape past the wheel at only 15 ips, while developing a relative head-to-tape speed somewhat in excess of 1500 ips. A reel containing only 4800 feet of tape (12½ inches in diameter) is then capable of recording a 1-hour program.

For television, the ability to record and play back high frequencies and wide bands is insufficient. It is *an absolute must* that in playback the signal be *properly timed*, with horizontal sync pulses occurring precisely every 63.5 microseconds, and vertical pulses every 16,667 microseconds. Small timing errors between recording and playback in video applications not only cause distortion, but more important, a loss of synchronization in all the receivers picking up the playback signal. Pictures reproduced under such circumstances would contain a side-to-side jitter, and would most probably roll. Such errors have to be prevented, not minimized, and even hysteresis synchronous motors are not accurate enough for the job, for both wow and flutter may be present. To bring all timing errors in the system to a final irreducible minimum, requires servo control of both the capstan motor and the motor driving the head wheel. Additional servo control is needed to ensure firm contact between the tape and the rotating heads. Color compounds the problem, but it is simpler to correct the signal itself rather than attempt to obtain the infinitely accurate control that would otherwise be necessary.

In practice, both the Ampex and RCA machines record a special control signal on a separate track near the bottom edge of the tape, at the same time the picture information is being recorded. In playback, this sync signal is used to control the speed of the machine. It may be convenient to think of this "control-track" signal as the electrical equivalent of the sprocket holes used in motion-picture work, but the analogy is not quite exact. The track does not pull the tape by itself, it merely controls the motor that does the pulling, and in so doing provides a much tighter control of speed variations than does a set of sprocket holes.

Several other problems also arise when picture signals are magnetically recorded. For example, in motion-picture work, frames are visible. This is not true of tape. Therefore, a pulse occurring once per field is placed on the control track during recording. This pulse identifies every vertical blanking period, and indicates where splices should be made if they are to be invisible to the viewer. However, these "field pulses", as they are called, cannot identify either the start or finish of a complete scene. For this reason, an extra track, known as a "cue track", is also recorded on the tape. Cue-track circuits are independent of the regular recording and playback, and channels may be set to record verbal comments for future reference while watching a playback of the recorded video signal.

There is also the problem of feeding the signal to the rotating heads during recording, and getting it out again in playback. Although there might be some advantage to operating the heads one at a time, this is too difficult, so a compromise is made. To reduce the machine's complexity, only a single set of heads

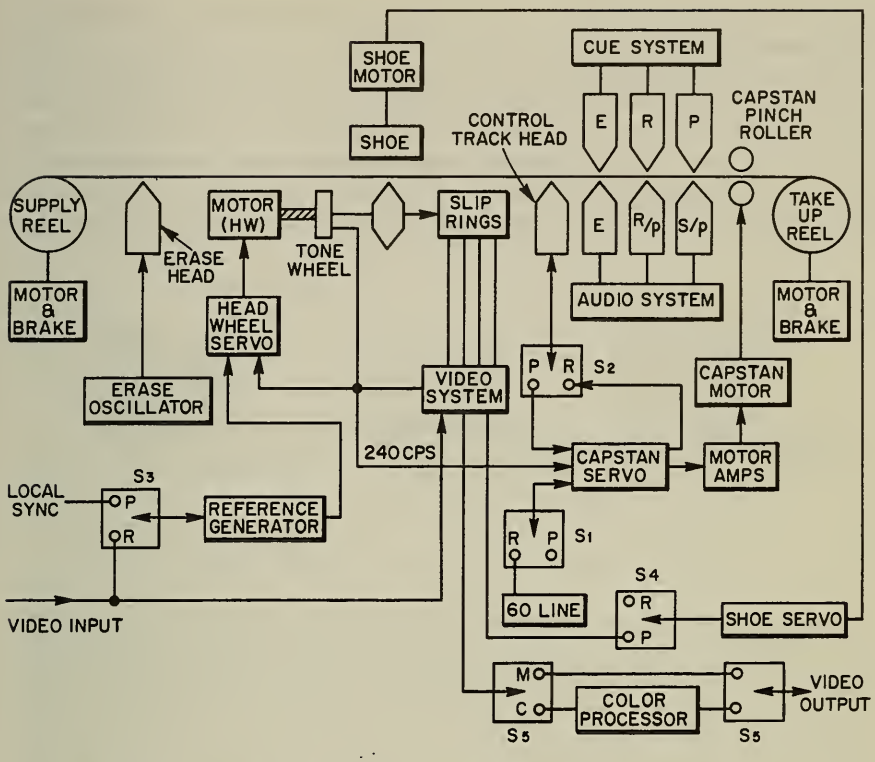


Fig. 6-1A. Modified block diagram of the RCA television tape recorder. *After RCA.*

is used for both recording and playback. In the record mode of operation all the heads are fed with the video signal simultaneously. For playback, a switching system reads out the head signals sequentially.

Block Diagram

Figure 6-1A is a modified block diagram of the RCA television recorder, and Fig. 6-1B illustrates the signal conditions on the tape during recording. The Ampex machine is essentially the same except for the servo system and the color corrector. It should be noted at this point that the RCA and Ampex machines *are fully compatible.* Tapes recorded on either machine may be played back on the other without difficulty.

In the diagram, the supply and take-up reels are shown at the sides near the top. Each reel has its own motor and is independently driven. In record or playback, this provides tension, and prevents slipping of the tape. In fast for-

ward or reverse, the reel motors drive the tape with the unwinding reel supplying tension.

In the record or playback modes the tape is unwound from the supply reel on the left, passing first over a 2-inch wide master erase head (actuated only in the record mode) and then on to the rotating head wheel, whose speed is 14,400 rpm, or 240 rps. During its passage over the heads the tape is curved by a vacuum shoe so that the entire 2 inches of tape width is in contact with the surface of the head wheel. The vacuum shoe also holds the tape tightly against the

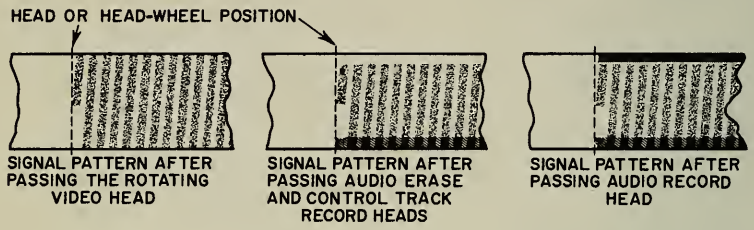

HEAD OR HEAD-WHEEL POSITION
SIGNAL PATTERN AFTER PASSING THE ROTATING VIDEO HEAD
SIGNAL PATTERN AFTER PASSING AUDIO ERASE AND CONTROL TRACK RECORD HEADS
SIGNAL PATTERN AFTER PASSING AUDIO RECORD HEAD

Fig. 6-1B. Signal conditions on tape during recording. *After Ampex.*

heads, tight enough that the heads dig slightly into the tape. This ensures the good contact necessary in magnetic recording. After leaving the rotating head wheel, the tape passes over the control-track head which records both the special synchronizing signal and the field pulse. Three audio heads (erase, record, and simultaneous playback), are next in line. The audio erase head (E) cleans a small path near the top of the tape, after which the audio signal is recorded by audio head R/P. For playback, the same head must be used to read out the audio signal in order to provide lip synchronization, but during the record mode it is possible to monitor the audio channel with the simultaneous playback head (SP).

The cue-track heads are located at the same position on the tape deck as the audio heads, but they record on the opposite edge of the tape. The cue track itself is quite narrow, a condition that creates difficulty at high frequencies. However, since this track is used only for voice, or timing tone signals, it is not necessary to provide high-quality reproduction, and an upper limit of 6 kc is satisfactory. Additionally, in order to reduce crosstalk from the adjacent control track, the bandwidth is reduced even more by deliberately cutting off the low-frequency end of the cue-track spectrum at 300 cps. This provides a signal-to-noise ratio of 34 db for the cue track, which is more than adequate for the purposes to which it will be put. In some machines, no erase head is provided for the cue system, and both record and playback functions are combined into a single head. Also, in some early models, the cue track was superimposed on the control track. Current models of both the Ampex and RCA machines utilize a separate, smaller, area for the cue track itself.

After passing over the combined cue and audio heads, the tape proceeds to the capstan and pinch-roller assembly which does the work of pulling the tape past the heads. From the capstan, the tape goes to the take-up reel, after first passing over an additional stabilizer or tape guide. Due to the servo control of the capstan, the timing accuracy of the transport portion of the machine is less than half a second error per hour between playback and record.

In the record mode, the capstan motor (at the right) is supplied with 60 cps from the power line. Switch S-1, relay operated, connects the power line into the capstan servo system where it is split into two phases 90° apart. Both phases are sent on to the motor amplifiers, two 70-watt units, that feed the two-phase capstan motor. The motor then drives the capstan, causing the tape to move through at 15 ips. For fast forward or reverse operation, the capstan motor receives no power.

The head-wheel servo at the center left ensures that the head wheel is always operating at 14,400 rpm. The three-phase head-wheel motor is driven, through amplifiers and phase splitters, from a stable R-C oscillator operating at 330 cycles. Attached to, and rotating with the head wheel, is a magnetic tone wheel — Ampex uses an optical wheel — which provides 240-cycle pulses, assuming the wheel is spinning at the correct speed. The 240-cps output from the tone wheel is fed to the head-wheel servo system. In the record mode, switch S-3 connects the incoming video signal to the reference generator for use as a timing reference. Horizontal sync pulses are stripped out of the video by this circuit, converted into 240-cps pulses, and fed to the head-wheel servo where they are compared to the 240-cps pulses from the tone wheel. If both signals are identical in frequency and phase, nothing happens. However, if the head wheel starts to speed up or slow down for any reason, the pulses from the tone wheel will be altered, and the two inputs to the comparison network will no longer be of either the same phase or frequency. As soon as this occurs, an *error* signal proportional to the difference between the two inputs is developed by the comparison circuit.

The error signal is used to change the power being fed to the head-wheel motor, thereby altering its speed in the opposite direction from the original change. In turn, this causes the tone-wheel output frequency to change again, and the new output frequency is once more compared to the reference generator signal. The action is continuous, and the smallest variation in the head-wheel motor is almost instantly compensated, resulting in the correct speed being maintained. The 240-cps tone-wheel signal is also sent to the capstan servo where, in record, it is changed to a more convenient waveform and applied to the control-track head through switch S-2. Within the capstan servo, too, the field pulse is added to the control-track signal.

Incoming video, in addition to feeding the reference generator, is also delivered to the video system. Here, it is converted into a vestigial sideband f-m signal, and fed to four recording amplifiers, one for each head. The amplifier outputs are connected to a bank of relays (not shown) that pass the signal on

to the heads for recording. A system of brushes and slip rings on the head wheel provides the final connection to the heads. Due to the combination of rotating heads and longitudinal tape motion, the video signal is recorded as a series of transverse tracks across the tape. The exact size and form of these tracks will be discussed later in this chapter.

In the playback mode, switch S-3 selects local sync (from a sync generator) as the timing reference. The reference generator converts this to 240 cps, and delivers it to the head-wheel servo. The same comparison process is repeated with this new reference, and the head-wheel speed is again held constant. During playback, the control-track head acts as a pickup, and switch S-2 feeds the resulting signal into the capstan servo, while the 60-cps power used previously is disconnected by switch S-1. At the same time, the 240-cps tone-wheel signal also arrives at the capstan servo. A special circuit in the capstan servo compares the frequency and phase of the tone-wheel signal to that taken from the control track. The resulting error signal controls a 60-cycle R-C oscillator that drives the capstan.

With the head wheel and capstan both operating at the correct speeds, the rotating heads now follow the tracks laid down in the record mode and pick up the recorded signals from the tape. Each head feeds its signal to the brush and slip-ring assembly, through the relay bank, and into the video system. Four separate channels, one for each head, are used to amplify the signals before they are combined into a single output by an electronic video switcher. The output of the video system is, for black and white, indistinguishable from the original recorded signal. Color signals are not quite identical to the original, and require further correction.

A separate circuit in the color processor checks for the presence of a color burst. Should a burst appear in the signal, this circuit actuates switch S-5 and routes the signal through the processor. When no burst is present, switch S-5 remains in the monochrome (M) position, and the processor is bypassed. Briefly, the color circuits compensate for small line-to-line variations that the head-wheel servo does not correct. For monochrome, these variations are unimportant, but with color they tend to shift the phase of the color subcarrier, resulting in a hue change. The color processor cancels these phase errors in the subcarrier, and at the same time performs another task. The overall recording and playback system tends to deform the color burst, so a new burst must be manufactured. A signal from the station's local 3.58-mc oscillator is used, together with a gating pulse derived from the horizontal sync. The pulse adds the new burst to the signal at the proper time, resulting in a standard color signal ready for transmission. The right side of switch S-5 feeds the signal out to the studio circuits.

There is, finally, one remaining circuit to discuss: the shoe servo. During the recording process the vacuum guide, or shoe, that holds the tape against the heads, is locked in position. As mentioned previously the heads dig into the tape surface, causing some slight stretching. In playback, if the shoe is im-

properly positioned, incorrect stretching, small as it may be, might cause a time displacement of the horizontal lines being reproduced by any one head. Furthermore, no two machines exert exactly the same pressure on the tape. So, if a composite tape made up of segments recorded on several different machines is

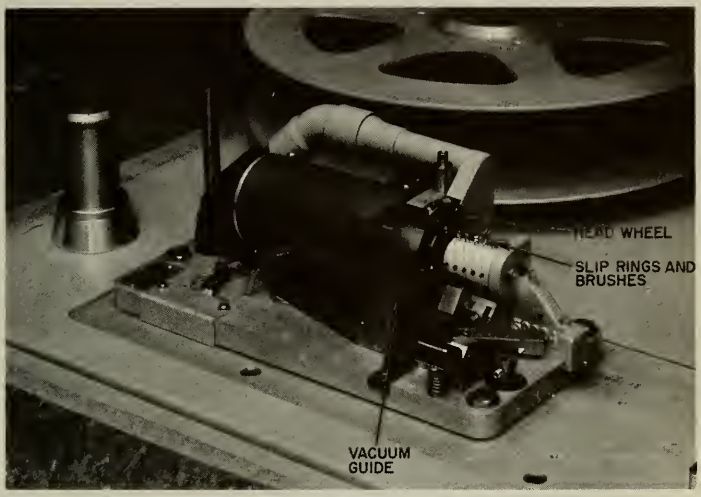


Fig. 6-2A. Ampex video head subassembly. *Courtesy Ampex Corp.*

to be played back, the head-to-tape pressure must be properly adjusted for each segment. This is done automatically by the shoe-position servo.

The shoe servo is fed with the playback signal through switch S-4 (in record, the servo is inactive). It then measures the time between successive horizontal sync pulses. If an error exists, a correcting voltage is applied to a motor which, through appropriate gearing, moves the vacuum shoe in or out the required amount. Manual controls are provided in the circuit to compensate for the effects of changing temperature or humidity.

Tape Transports

Let us now examine the transport mechanisms of the Ampex and RCA machines. Both machines are push-button operated from a separate control panel either on the machine, or at a remote location. There are no operating controls on the tape decks themselves.

On both machines, the rotating video heads and associated equipment are built as subassemblies (Fig. 6-2A). The head wheel in these assemblies rotates partly inside the vacuum shoe, or guide. Figure 6-2B is a cross-section representation of the guide and head wheel. Note that at the bottom of the guide

there is a support that prevents tape from sliding down too far on the head wheel. The vacuum chamber establishes suction in the center region of the tape to aid in curving it properly. The head wheel itself is 2 inches in diameter, and the four heads are located on its circumference as near 90° apart as possible, with an error of less than 30 seconds of arc for each position. Each head is re-

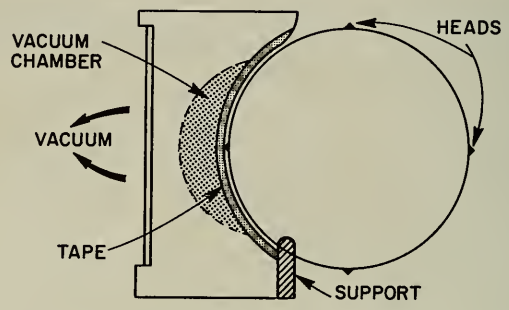


Fig. 6-2B. Cross-section of vacuum guide and head wheel. *Courtesy Ampex Corp.*

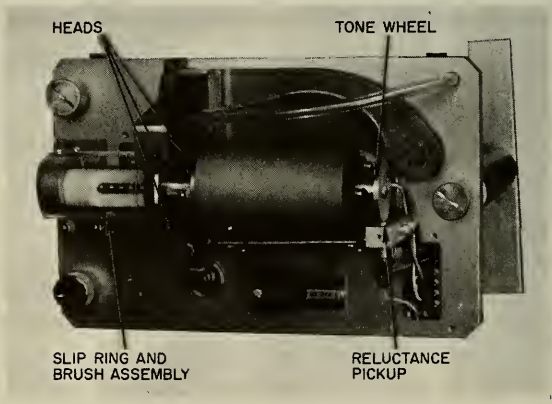


Fig. 6-3. Motor, head wheel and tone wheel of the RCA television tape recorder. *Courtesy RCA.*

cessed into the head wheel as shown in Fig. 6-3, and only the tip containing the gap protrudes.

Video heads are tiny assemblies, as comparison to the pencil in Fig. 6-4 indicates. Note too, the relative size of the coil. Construction details of the RCA heads are shown in the cutaway view (Ampex heads are similar). Nonmagnetic material is used in the clamping block for obvious reasons. Gap width is 80

microinches, ± 20 microinches, obtained with a thin spacer between the pole tips. The gap length is 1/100 of an inch, or 10 mils. At the moment, the heads are good for something more than 100 hours of operation, but eventually the pole faces wear down. Oddly enough, for a period of time the heads improve with wear. However, when the wear becomes excessive, i.e., the gap depth is almost zero, the resulting picture output starts to deteriorate. One wire from

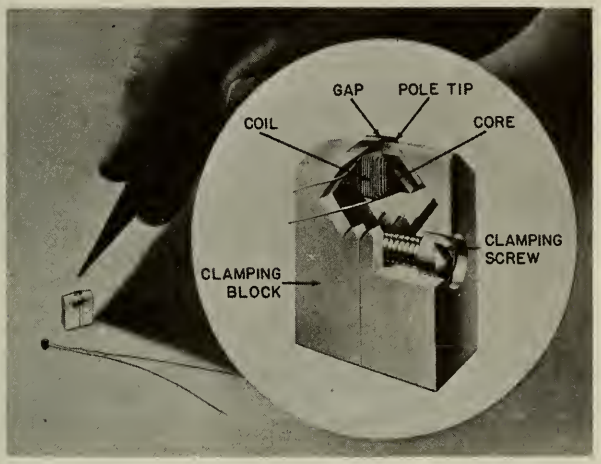


Fig. 6-4. Construction of the RCA video heads. *Courtesy RCA.*

each head is connected to a slip ring on the head-wheel shaft, making contact with a silver graphite brush, while a 5th slip ring is used as a common connection for all the heads. Each head has an inductance of 25 microhenries at 100 kc. In conjunction with the stray capacitances of the system, the heads are resonant at 6 mc in record, and 6.5 mc in playback. These resonances are used as an aid in obtaining the desired frequency response.

In the RCA TRT-1A machine, an extra tone wheel containing a small notch is mounted on the same shaft as the head wheel. A reluctance pickup is placed adjacent to the tone wheel (shown at one end of the motor in Fig. 6-3), and is connected to a source of dc. As the notch sweeps across the face of the pickup, a change occurs in the magnetic pattern established by the dc, resulting in an output pulse. Due to the small size of the notch, the period of the pulse is quite short. Rotation at the correct speed produces 240 pulses per second. The circuit used with the pickup, and the resulting output, is illustrated in Fig. 6-5, part (A).

In the Ampex machine, the head wheel itself is painted black and white in 180° segments, as indicated in Fig. 6-5, part (B). A light is focused on the head wheel, and reflections from the wheel as it rotates are picked up by a photo-

electric cell. When head-wheel speed is correct, the output of the cell is a square wave at 240 cps, inasmuch as the wheel rotates 240 times each second.

Both machines use three-phase motors for the head wheel, the Ampex motor operating with 240-cycle power, while the RCA is operated from a 330-cycle source. A blower system is incorporated in the head-wheel assembly to aid in cooling both motor and wheel. Acting additionally as a vacuum cleaner, the

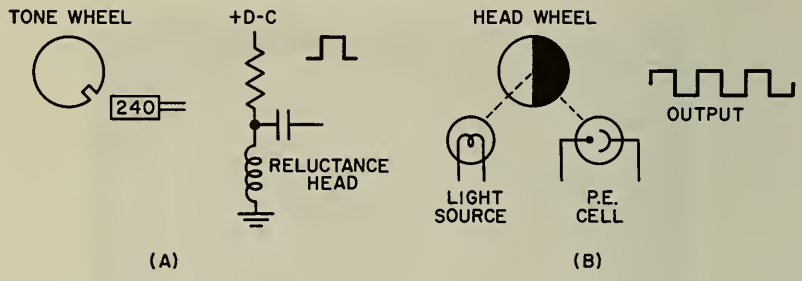


Fig. 6-5. (A) Operation of the RCA tone wheel. (B) Operation of the Ampex optical head wheel.

blower also removes oxide dust and chips that are flaked off the tape as it passes over the head wheel.

The control-track head is a part of the video head subassembly, although it does not move. It is located just past the head wheel, down the tape, and records its signal on the lower edge of the tape. No erasure is needed for this track as it records only a single frequency component, longitudinally.

On both tape decks, the audio heads are located between the head-wheel subassembly and the capstan. The audio erase head wipes the recorded video signal off the tape at the top edge, thereby providing space for the audio track. The combination record-playback head is placed 9 inches down the tape from the video heads, so that on a recorded tape, the sound track leads the picture by this amount. A dual-track head for stereophonic sound recording may be used in place of the standard audio head. The Ampex machine does not include a third audio head for monitoring purposes during recording. As a convenience, the cue-track heads are located in the same stack as the audio heads. Covers are fitted over all the heads as illustrated in Figs. 1-3, 1-4, and 6-7.

Both tape decks are fitted with a counter calibrated in either feet, or minutes and seconds. In general, tape editing is facilitated with a footage counter, but on the other hand, producers and directors who must tailor a program to fit an available time period, may find a time counter preferable. For use with other scanning standards (British or European), the counters may be changed to provide accurate measurements with the somewhat different tape speeds that become necessary.

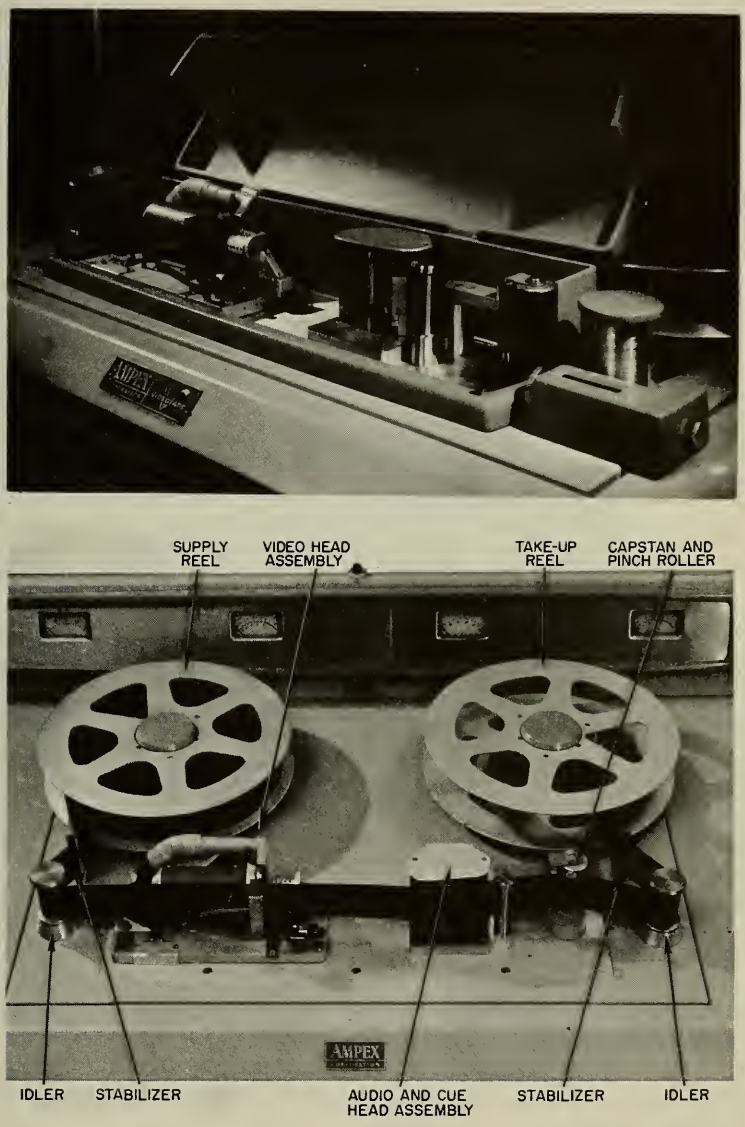


Fig. 6-6. Tape transport of the Ampex VIDEOTAPE television recorder, with head-cover open. Footage counter and erase head not shown here, can be seen in Fig. 12-1. *Courtesy Ampex Corp.*

Photographs of the Ampex and RCA tape decks appear in Figs. 6-6 and 6-7. On the Ampex mechanism, tape from the supply reel passes over a tension arm capable of swinging through a wide arc, and then over an idler post. Flanges on the idler, position the tape vertically, and prevent up and down motion of

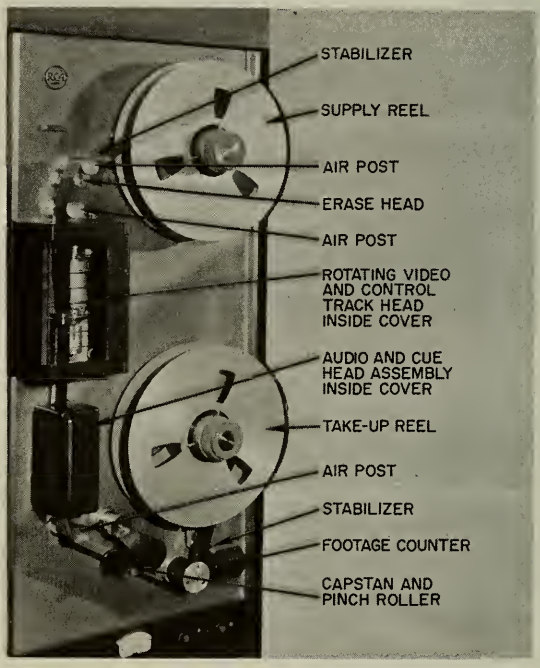


Fig. 6-7. Tape transport of the RCA television tape recorder. *Courtesy RCA.*

the tape. A similar arrangement is used at the take-up reel, and the combination effectively smoothes out variations in tape motion.

The RCA recorder also uses a swinging tension arm at each reel to remove speed variations. In association with the arms, are stationary tape guides employing the technique of *air flotation.* Air, under pressure, is forced through a number of tiny holes in the post. The tape is thus lifted off the surface a slight amount, and touches the guide only at the edges, where flanges are used to prevent the tape from riding up or down on the guide. Only a small amount of guiding pressure is needed with this arrangement, and it results in accurate positioning. The air guides do not rotate, as the air effectively isolates them from the tape. A third air guide appears on the deck just before the audio heads.

Operation in the record or playback mode is essentially the same for each

recorder. Pressing the appropriate button starts tape through the machine. The solenoid-actuated brakes are released, and resistance is added to the motor circuits to reduce their torque. The supply-reel motor provides tension on the tape, while the take-up wheel rotates just fast enough to wind the tape delivered to it from the capstan. When the tape reaches the correct speed (approximately 2 seconds after starting) the vacuum guide moves into position so that the tape will contact the rotating heads. Pressing the stop button activates the brakes and the machine comes to a halt. Between the time the stop button is pressed and the machine actually stops, 3 inches of tape pass the video heads. For ease in pulling tape from a reel for splicing, or threading, a hand-operated brake release is incorporated into the Ampex tape deck.

For fast forward or reverse operation the capstan and pinch-roller are separated, and the capstan motor is disconnected from its source. In the RCA machine, the head-wheel motor is stopped, and the vacuum guide retracts from the head wheel. A tape lifter is also actuated in the RCA machine, lifting the

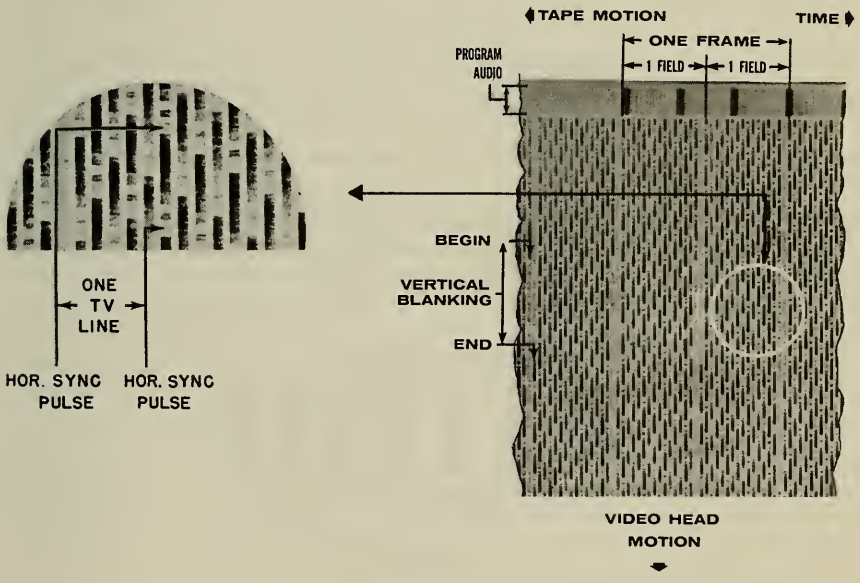


Fig. 6-8. Typical tape-track patterns. *Courtesy RCA.*

tape off the heads for fast operation. On both tape decks, the torque of the reel motors is altered by adding or removing resistance from their circuits. The motor with the larger torque rotates, and pulls the tape through the machine. Both machines permit alternate operation in forward or reverse without the necessity of first stopping, but they cannot be placed in record or playback from

either fast speed, unless the tape motion is first stopped. On the Ampex machine, fast operation is controlled by a pair of push buttons, one for each direction. The RCA machine provides a variable speed rewind, or forward operation. Tape may also be rewound directly from reel to reel (off the normal tape path) in the RCA machine.

Video Track Patterns

The magnetic patterns recorded on the tape by the various heads may be examined visually. This is accomplished by coating the recorded tape with a carbonyl iron suspension, and transferring the resulting pattern to a sheet of paper with transparent tape. Figure 6-8 is a photograph of a typical section of recorded tape. To understand this pattern, suppose we follow the recording process step by step.

In the record mode, the modulated video signals are fed to all four rotating heads simultaneously. The combination of capstan and head-wheel speeds is

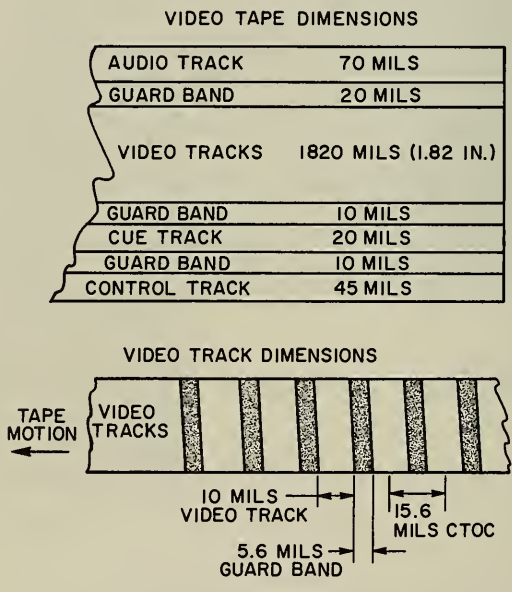


Fig. 6-9. Track dimensions of a video recording.

such that the capstan moves the tape 62.4 mils for each revolution of the head wheel, or 15.6 mils for each quarter revolution. In a quarter revolution, one head will be swept across the tape, recording a transverse track. The top and bottom of the track are displaced from each other by 15.6 mils, the distance the tape

moves for one head sweep. As a head leaves the bottom of the tape, another is starting to record a second track at the top. The track centers are therefore spaced 15.6 mils apart. The gap length in the rotating heads is 10 mils, so each track occupies this much space, leaving the remaining 5.6 mils as a guard band between adjacent tracks.

Now, the vacuum guide curves the tape into an arc of 113° (120° in the Ampex machine). Calculations show that this arc length, in conjunction with the velocity of the head wheel, causes 18.4 horizontal lines of video information to be recorded along any one track. These are seen in the pattern as alternate dark and light segments. The enlarged portion of the pattern illustrates the relative spacing for one horizontal line. Each horizontal video line requires 0.1 inch, or 5.5° of arc on the tape.

Due to the length of arc in the tape, it seems clear that if the heads are spaced only 90° apart, there must be some duplication of information. Before any head leaves the bottom of the tape, the next head has already started. Thus, the first two horizontal video lines along any transverse track, are duplicates of the last two on the preceding track. This need be of no concern, for in playback the overlap will be removed, and an average of 16 lines per track will be read out.

In the direction of tape motion, 16 transverse tracks comprise one field. A frame is therefore 32 transverse tracks, or ½ an inch of tape. Vertical blanking intervals between fields are visible in the photographed pattern.

After the video tracks have been recorded, the other 3 tracks are added. The control track, as specified previously, is placed at the bottom of the tape, as is the cue track. Field pulses, not shown in the diagram, also appear on the control track. Program audio is recorded longitudinally at the top of the tape, and a narrow guard band (20 mils) appears between the audio track and the start of the transverse video tracks. Failure to provide a guard band at this point might cause the audio system to reproduce a 960-cps component along with the audio. The guard band is produced by making the gap length of the audio erase head, slightly larger than that of the combination record-playback head.

The relative size and spacings of all 4 tracks is shown in Fig. 6-9. The values shown are those used in both the RCA TRT-1A and the Ampex 1000-B VIDEOTAPE recorders. The guard bands are sufficiently wide to prevent crosstalk between tracks.

Chapter 7

SERVO SYSTEMS

Introduction

A servomechanism is a form of *control system* in which the output of a device controls its operation. The word "servo", from the Latin, means, literally, slave. Thus, a servo system is a slave to its own output. In today's technology, many servo systems are commonplace, but we often overlook them. Thermostats used with home heating equipment, and automatic transmissions in cars, are typical servo systems. In many respects even the human body is a servomechanism.

Control systems may be simple, or highly complex. For convenience they are grouped into certain categories. An "either-or" system is perhaps the simplest control that can be built. A light switch on a wall is a typical example of an "either-or" control system. *Either* the light is on, *or* it is off. *There is no in between value* and such a system is not flexible. If flexibility is desired, a "continuous" system must be used. The dimmer for the dashboard lights of a car, for instance, is a continuous control system. Turning the knob to its limit in one direction turns the lights off completely, while turning it to the maximum in the opposite direction makes the lights quite bright. In between these limits, however, an infinite number of choices may be selected, each changing the intensity of the light a slight amount.

Control systems may also be classed as "open-loop" or "closed-loop" systems. In an open-loop (or open-cycle) system, the control operation is completely independent of the result, while in the closed-loop system the control operation is determined by the results. The wall switch is an open-loop control. A house thermostat, on the other hand, is a closed-cycle control system. Consider this thermostat for a moment. When the temperature in the house decreases to a preset value, the thermostat closes a switch, turning on the heating system. The

system remains on till the temperature has risen a few degrees, at which time the thermostat shuts down the unit until the temperature again drops. The room temperature therefore controls the operation of the furnace on a continuing basis.

A servo system is basically a closed-loop control system in which *feedback* plays an important part. The block diagram of Fig. 7-1 illustrates a typical servo system. The data transmission unit gives initial instructions to the machine, and acts as a reference signal to which the output is later compared.

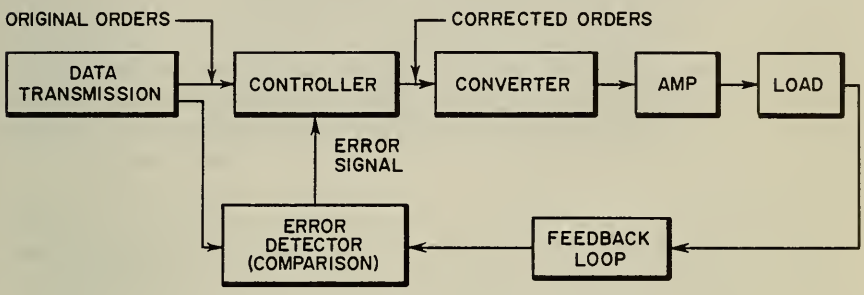


Fig. 7-1. Diagram of a typical servo system.

For example, the adjusting knob on a thermostat transmits data as to the desired temperature. The controller does the actual work of operating the system. In a heating arrangement this would be the bimetallic element of the thermostat. Converters, if used, merely change the form of energy utilized by the system. In some systems, when insufficient power is developed by the controller, an amplifier is added. The load, finally, does what the controller has instructed it to do, and also sends a message back to an "error detector" through the feedback loop. This informs the controller of the load's operations.

The error detector of a servo system is used to compare the feedback signal to the original data. If the load is performing exactly in accordance with the original orders supplied to the controller, the detector output is zero. On the other hand, should the load be incorrect in any way, the error detector measures the difference between the original input signal and the feedback signal. This difference is called the *error signal.* It is fed into the controller along with the original orders, thereby adding information as to the correction needed at the load. As the load conditions change, any information fed back to the error detector also changes, as does the error signal. As the load gets closer to proper operation, the error signal represents less difference, consequently it becomes smaller and smaller, exerting less and less influence, until eventually, when the load is operating correctly, the error signal drops to zero. Should any subsequent change occur at the load, an error signal once more is generated by the detector. In this manner, instant by instant, the controller is always able to maintain the conditions being dictated by the data transmission system.

The operating characteristics of a servo loop are indicated in Fig. 7-2. After the system has started, inertia tends to make the output rise above the desired point, as at t_1. The instant this occurs, the error signal causes the system to reverse itself, and the output accordingly swings in the other direction. However, inertia again takes over, causing the system to move too far in the opposite direction, as at t_2. Once more the error signal supplies a correction, and the output swings up, but again, too far.

Two possibilities now exist. If the system is inherently unstable (usually due to some undesired positive feedback), the variations above and below the axis become more pronounced, and the system starts to oscillate violently, making it useless for control functions. Conversely, if the system is well designed, the fluctuations around the desired operating point die out, and the system locks itself to the desired conditions. An in-between condition, known as *hunting*, may also occur. This is actually oscillation, but to a limited degree, in which the peaks of the output vary only slightly around the operating value. An example of the effect of hunting, as it appears in the video recorder, is shown in Fig. 7-3.

For continuous servo systems, hunting should be present only after an abrupt change in input, and then only for a short time. When relatively rapid changes occur in the error signal, the hunting may appear to be continuous, but if it is of small amplitude, it need not be taken seriously.

An important additional requirement of a servo system is that the speed of its response must be faster than the process being controlled. For example, in

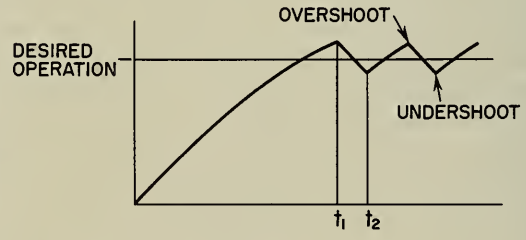


Fig. 7-2. Servo-system characteristic curve.

order to properly control a motor operating at 1400 rpm, a servo system must be able to respond to changes that occur more rapidly than 1400 times per minute.

With these thoughts in mind, let us now examine the servo systems of the Ampex and RCA machines. Essentially, these systems control both the speed and position of the tape as it moves through the machine. Figure 7-4 illustrates the result during playback if the tape is not correctly positioned on the heads.

For construction convenience in both machines, certain parts of each servo system have been placed in other assemblies. Low impedance interconnecting cables are used to feed the necessary signals from one assembly to another. To

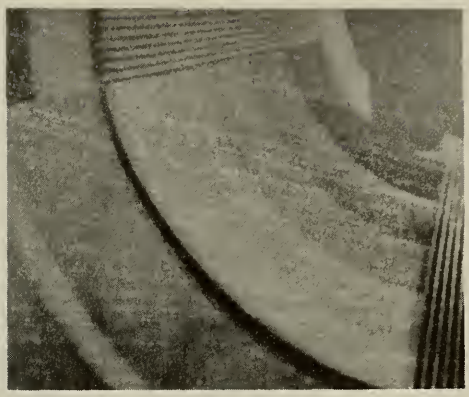


Fig. 7-3. Illustration of head hunting, or a horizontal shifting back and forth of the reproduced picture, caused by undesirable fluctuations in speed of the head. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

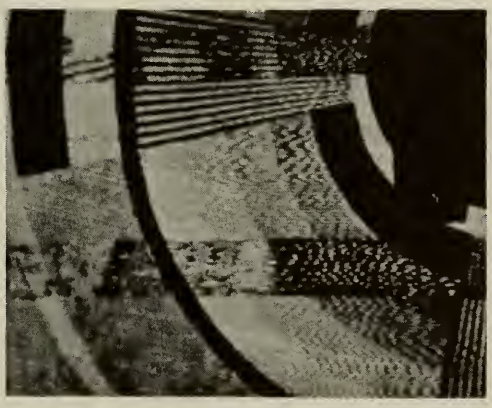


Fig. 7-4. An illustration of mistracking, resulting in deterioration in picture quality, and caused by errors in positioning of the tape with respect to the head. The degree of impairment may vary from a reduced signal-to-noise ratio through heavy moiré to a complete loss of picture. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcastrs and the Bell Telphone System) and CBS.*

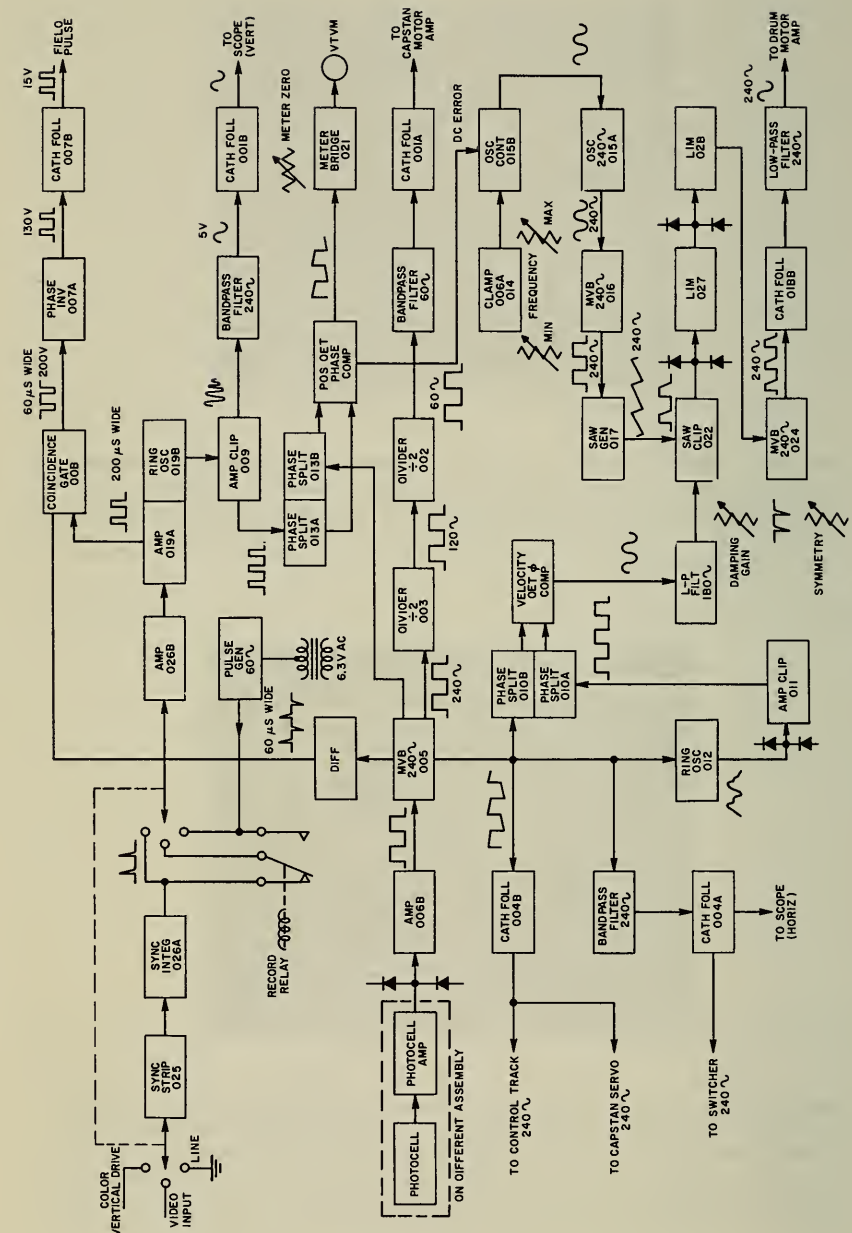


Fig. 7-5. Ampex drum-servo unit.

provide matching at the sending end, a cathode follower (see Chapter 11), a form of amplifier in which the output is taken from the cathode rather than the plate, is employed. The output voltage of a cathode follower is less than its input voltage, so the tube cannot be classed as a voltage amplifier. It does, however, act as a power amplifier, and it provides quite low output impedances, as well as a greater degree of isolation between input and output than a conventional amplifier. In the following discussion, each system will be analyzed completely, regardless of component locations, although these will be indicated.

Ampex Drum-Servo Control Unit

In the Ampex recorder, the head-wheel servo system is contained in the *drum-servo control unit.* (In earlier models, this was known as the master-control unit.) Some of the circuits in the drum servo also act as processors for the various control signals used in the other servos.

Briefly, in the Ampex machine the head-wheel motor is driven by a multivibrator operating at 240 cps. The output is filtered, amplified, and fed to the drum-motor amplifier. The amplifier splits the signal into three equal phases, each 120° apart, and feeds these to the three-phase head-wheel motor. The servo-control system may be referred to any of three basic timing references, 60 cps, local sync, or color sync. A tracking control is located in the circuit to ensure that in playback the heads travel over the same tracks laid down on the tape in the record mode.

Referring to the block diagram (Fig. 7-5), the video signal is fed into the unit at the top left. A switch appears at this position, ganged to another section further on. This switch permits selecting the timing reference. In record, the switch is normally in the video position, permitting the video signal to enter tube No. 13025. The first two digits of the Ampex tube numbering system are used as a code to indicate the chassis on which they are located. For ease in referring to the diagram, these have been omitted. Tube No. 13025 is therefore shown as tube 025. This tube, a 6AW8, is a video amplifier, biased to remove part of the video signal while retaining the sync. The remaining signal is passed on to the next stage, tube 026A, one half of a 12AT7. The remaining video is stripped out and the sync pulses integrated, thereby disposing of the horizontal components. If the switch is placed in the color sync position, the 1st stage acts merely as an amplifier, as no video signal appears in the circuit. In the line position the two stages are inoperative since the input is grounded.

Regardless of switch position, the second section of the switch selects some form of 60-cps pulse. In the line position, (or video, if the relay just below the switch is not energized), the pulse is obtained through a neon-bulb pulse generator (see Chapter 10), supplied with 60 cps from a transformer, connected to the line. In the video position (with the relay energized) or in color, the switch selects the output of integrator 026A. The selected pulse is delivered to amplifier 026B, the other half of the 12AT7, and on to amplifier 019. The first

half of this stage amplifies and clips the pulse, and sends it to the other half, a ringing oscillator tuned to 240 cps. The incoming 60-cps pulse triggers the ringing circuit every 4th pulse, producing a train of decaying sine waves as shown in the diagram. The output of the ringing circuit is fed into clipper-amplifier 009, providing an output of almost symmetrical square waves. These are sent to phase splitter 013A to develop a push-pull signal for use in the position detector phase-comparison circuit. The signal from clipper-amplifier 009 is the timing reference signal for the head-wheel servo. In addition to the position detector, the reference signal also feeds a bandpass filter that converts it into a sine wave, at 240 cps. Cathode follower 001B then passes the wave on to the built-in oscilloscope for testing purposes.

Now, examine the circuits beginning at the center left. The photoelectric cell picks up a 240-cycle square wave from the painted head wheel, as described in Chapter 6. This is amplified in a separate stage located on the *record-reproduce amplifier* chassis. From there, it is delivered (via cable) to the diode clippers (see Chapter 11) shown. These reduce the amplitude to 1 volt and then feed the signal to amplifier 006B. The resulting output square wave of this amplifier is used to trigger multivibrator 005, whose output is nominally a square wave at 240 cps (if the head wheel is at the correct speed), 150 volts peak-to-peak. One output connection of multivibrator 005 delivers the wave to phase-splitter 013B, producing a push-pull signal that is also fed into the position detector.

The phase-comparison network (see Chapter 10) produces a 480-cps rectangular wave from the two 240-cps waves fed into it. One edge of this 480-cps wave corresponds to the rise or fall of the reference wave (the wave produced from the video signal), while the other edge corresponds to the rise or fall of the photocell signal.

Now, if the output wave from the phase-comparison circuit is symmetrical, it is a square wave with an average value of zero. However, if the wave is not exactly symmetrical, a d-c component will appear, either positive or negative, depending only upon that portion of the wave occupying the greater period of time. This d-c component is the error signal used to control the head-wheel motor circuits for errors in head-wheel position. A metering circuit (tube 021) is added to indicate the amount and polarity of the error signal developed by the position detector. The meter is calibrated to show the amount of error in the drum position with respect to the selected reference signal.

Control of the head-wheel motor is accomplished by feeding the positional error signal to oscillator control tube 015B. The control tube inserts capacity into the circuit of Colpitts oscillator (see Chapter 10) 015A during a small portion of one cycle of the oscillator output signal. The output frequency of the oscillator is determined by the length of time the capacitor is placed in the circuit, but this time is established by the control tube (015B), in turn operated by the error signal. To sum up, the oscillator frequency is determined by the amount and direction of the positional-error signal. If the error signal is 0, the oscillator operates at exactly 240 cps. If the error signal is positive, the oscillator

frequency increases (by as much as 12 cps for a 1V error signal), and if the error signal is negative, the frequency decreases a similar amount.

For accurate control, sudden shifts in speed of the head wheel must be avoided. To prevent these from occurring, the oscillator control is clamped by tubes 006A and 014. Two controls, MIN. FREQ. and MAX. FREQ., set the limits of excursion for the oscillator frequency by limiting the plate voltage of the control tube. Sudden, sharp changes therefore, have no effect on the oscillator, but if a change persists, it causes the clamping level to change gradually, making the head wheel alter its speed accordingly.

Continuing on, oscillator 015A is used to trigger multivibrator 016, producing a square wave. The output of the multivibrator is differentiated to provide a series of positive pulses which then trigger sawtooth generator 017. This is sent on to sawtooth clipper 022 to set up the exact timing needed for the head-wheel motor. The action is described below.

Returning to multivibrator 005, an additional output is delivered to phase splitter 010B, which then sends the signal on to the velocity detector phase-comparison network. Another output from multivibrator 005 is sent to ringing circuit 012. The output of this ringing circuit (a sine wave) is clipped through the middle by the diodes, resulting in a 240-cps square wave approximately a quarter-cycle (90°) out of phase with the original input. The actual phase angle differs from 90° by an amount proportional to the difference between the photocell output frequency, and 240 cps. The shift is generated by the ringing circuit itself, which is antiresonant at 240 cps. (Feeding any signal not exactly at the antiresonant frequency into an antiresonant circuit, produces a phase shift.) If the photocell output is exactly 240 cps, indicating correct head-wheel speed, the phase shift is, of course, 0°, and the output of the ringer is just 90° out of phase with the input.

The output square wave from the ringing circuit and diodes is amplified by tube 011, fed to phase splitter 010A, and then to the velocity detector phase-comparison network, operating in the same manner as the position detector. Since two signals at 240 cps are fed into this network, the output becomes 480 cps, roughly square, at 10 volts, peak-to-peak. Should the photocell output frequency differ from 240 cps, the output of the velocity detector becomes non-symmetrical. Thus, a d-c component appears, with amplitude and polarity proportional to the difference in frequency between the photocell and 240 cps. The output of the velocity detector is sent to a low-pass filter which integrates the square wave slightly, and removes any 240 or 480-cps components. If, at any time, the photocell output frequency changes, the d-c error signal must also change. The rate at which such changes occur will be much lower in frequency than 240 cps, and they are capable of passing through the filter. The instantaneous output of the filter is therefore proportional to any instantaneous difference between head-wheel speed and 240 rps (or 240 cps). This output from the filter is sent to grid 1 of sawtooth clipper (see Chapter 10) 022 where it combines with the signal from sawtooth generator 017.

Sawtooth clipper 022 is a pentode. The sawtooth signal from generator 017 is fed into grid 3 of the clipper. Assuming no signal appears on grid 1 from the velocity detector, the output is a sawtooth of 75 volts, peak-to-peak, centered on a d-c axis of approximately 130 volts. A pair of crystal diodes are connected to the output, one biased at 129 volts, the other at 130 volts. Between them, they slice a 1-volt section out of the sawtooth output, as indicated in Fig. 7-6, part (A). If now, a signal is placed on grid 1 by the velocity detector, the d-c

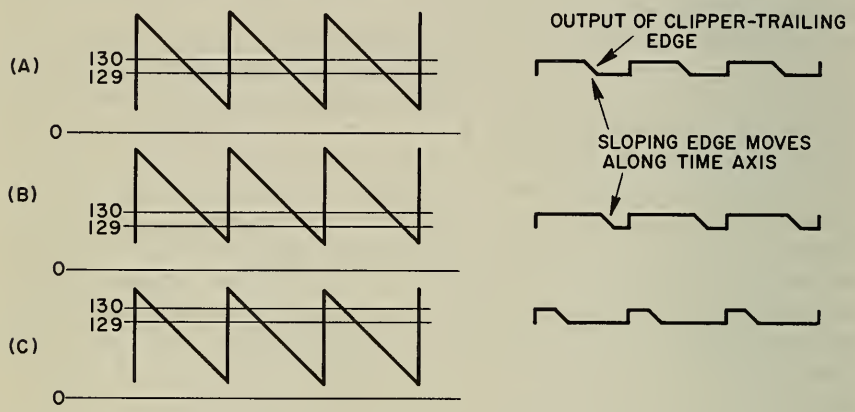


Fig. 7-6. Operation of the Ampex sawtooth clipper.

axis of the output sawtooth will vary, although the sawtooth itself will not change. Furthermore, the bias on the diodes is fixed, so as the d-c axis shifts, the portion of the sawtooth sliced out by the diodes also varies, but remains 1 volt in amplitude.

To illustrate, suppose the error signal on grid 1 is made slightly negative. The d-c axis of the output then shifts up to, say, 150 volts. The clippers now slice out a lower portion of the sawtooth, as shown in part (B) of the figure. Similarly, if the grid 1 signal is positive, the d-c axis shifts downward, and the sliced out segment is near the top of the wave, but still at 1-volt amplitude, as indicated in Fig. 7-6, part (C). Starting from the fast rise of the sawtooth, it becomes apparent that the trailing edge of the clipped section moves back and forth along the time axis in accordance with the signals on grid 1, moving to the left for decreases in grid 1 voltage, and to the right, for increases in grid 1 voltage. Simultaneously, the position of the grid 3 sawtooth along the time axis is itself determined by the positional error operating through oscillator 015. The resulting output trapezoid therefore has a trailing edge whose time axis position is dependent upon both positional and velocity errors. The "damping-gain" control permits adjustment of the circuit.

The sloping edge of the sawtooth clipper output is not accurate enough to

trigger the final oscillator. Consequently, it is amplified, clipped, and amplified again in stages 027, 028, and another pair of diodes. This converts the wave into a series of pulses that are differentiated and used to trigger multivibrator 024, whose output is a square wave at 240 cps, with a leading edge determined by the overall error signal. The symmetry control is used to ensure squareness. Cathode follower 018B feeds the wave into a low-pass filter. Inasmuch as a square wave is the sum of a vast number of sinusoidal components, harmonically related, the filter output is a sine wave at 240 cps. The relative phase of the wave is fixed by the combined position and velocity errors. This sine wave is sent on to the drum-motor amplifier, split into three phases, amplified, and fed to the head-wheel motor. The black and white segments of the head wheel now act as a feedback source, and send back information about the head-wheel operation, to the drum servo.

Let us now return to multivibrator 005 and examine its other outputs. One of these goes to cathode follower 004B to supply a 240-cps square wave to both the control-track circuits and the capstan-servo system. Another circuit, comprising a filter (to convert the square wave to a sine wave) and cathode follower 004A, feeds a 240-cps signal to the video switcher for use during playback, and also provides a sine wave for the test oscilloscope. Still another output is taken from multivibrator 005 to feed a pair of cascaded binary counters, tubes 003 and 002, that divide the frequency down to 60 cps. This 60-cps signal is then fed to a 60-cps bandpass filter to convert it into a sine wave that is applied to cathode follower 001A. The output of 001A is sent to the capstan-servo system for use in driving the capstan during the record mode.

A sixth, and final, output, is taken from multivibrator 005 to generate the field pulses. The square-wave output is differentiated and sent to coincidence gate (see Chapter 11) 008. Gate 008 also receives pulses from amplifier 019. The gate tube is normally cut off, but it operates whenever a timing pulse from amplifier 019 appears. Thus, every 4th pulse from the differentiated output is passed through the gate, *if it coincides with the time the gate is operating*. The gate output, a series of pulses occurring once per field, is then inverted in tube 007A and fed through cathode follower 007B to the control-track recording circuits. In the event the machine is out of sync with its reference, no field pulses are generated, because the gate operates at the wrong time and the differentiated interpulses from 005 cannot get through.

RCA Head-Wheel Servo System

The RCA head-wheel servo system is somewhat different from the Ampex circuit, but it is designed to do the same job: control the speed of the head wheel. Three separate units, the *reference generator*, *tone-wheel amplifier*, and *head-wheel servo*, are included in the overall system. A stabilized R-C oscillator together with a phase-shift network and two 70-watt amplifiers, drives the head wheel. In the record mode, horizontal sync from the incoming video is used to

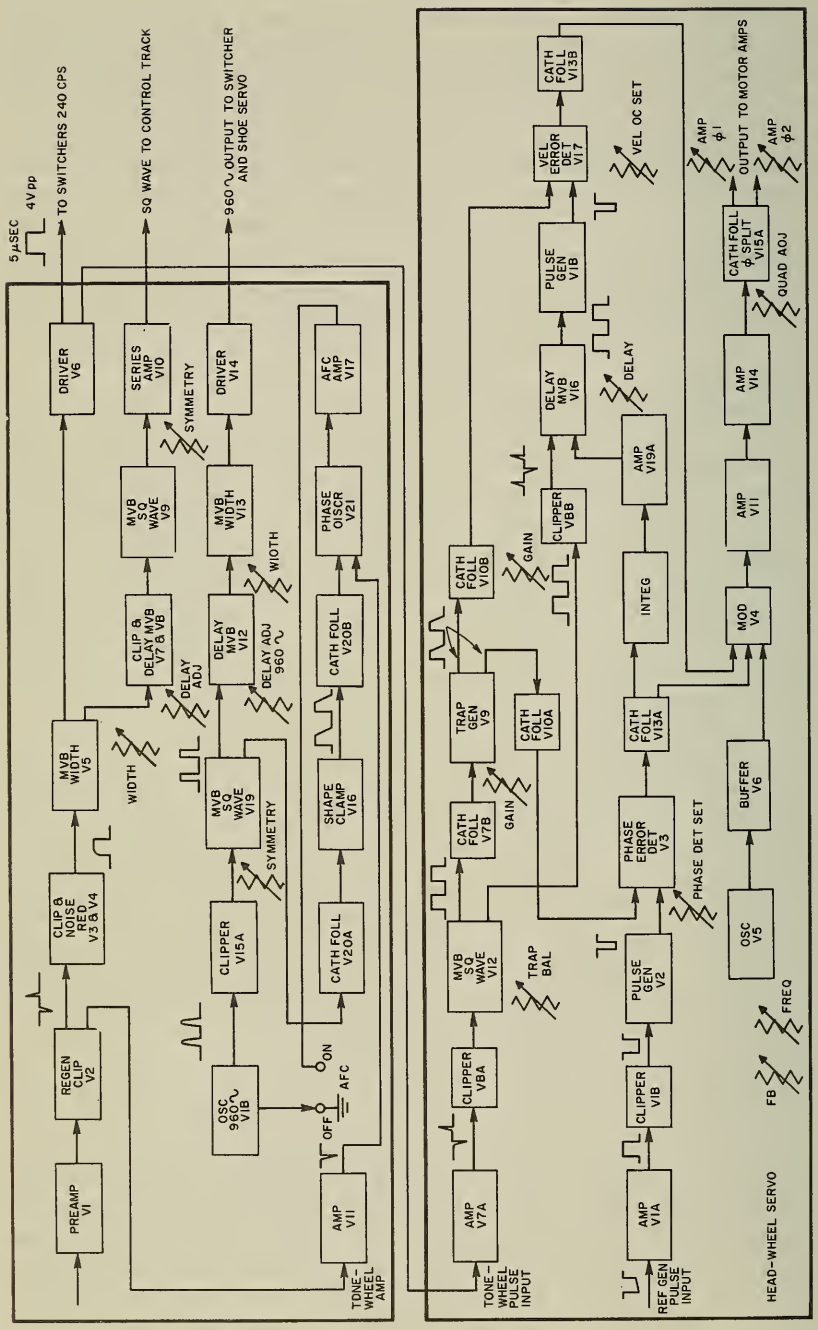


Fig. 7-7. RCA head-wheel servo.

obtain a 60-cps signal for comparison with the tone-wheel signal. In playback, either horizontal drive from the station sync generator, or 60 cps from the power line, is used for developing this reference signal. The head-wheel motor is a synchronous, hysteresis type, designed to operate near 300 revolutions per second, but its speed is held back to 240 rps by the servo system, which delivers just enough power to exactly balance the load at 240 rps. For test and setup purposes, the motor is operated synchronously with 240-cps power.

Figure 7-7 is a block diagram of the RCA head-wheel servo circuits contained in the tone-wheel amplifier and head-wheel servo subassemblies. The reference generator, not shown in the diagram, consists of a transistorized chain of frequency multipliers, dividers, and relay circuits that produce the 60-cps pulse used as a timing reference, and the field pulse that is recorded on the control track to indicate vertical blanking intervals.

Starting at the top left, signals developed by the reluctance pickup associated with the tone wheel are fed into the tone-wheel amplifier. These pulses are amplified in stage V1 and sent on to regenerative clipper V2, used to sharpen the pulse for the circuits that follow. One output from V2 is fed to a noise-reduction amplifier and clipper, a combination that provides a single, positive, noise-free output pulse, as indicated on the diagram. This pulse triggers width multivibrator V5, whose output is a rectangular wave (adjustable by the control indicated) having a positive-going pulse exactly 50 microseconds wide. Width multivibrator V5 delivers its pulses to two points, one of which, driver V6, feeds them out to the head-wheel servo and the switchers. The second output from V5 is sent to multivibrator V7. This stage inserts a 1080-microsecond delay in the pulse timing (so that the control-track circuits will be properly phased with the head wheel), before delivering it to V9, another multivibrator. V9 is adjusted with the symmetry control to provide a mark-space ratio of 1 : 1, or, in other words, a square wave, at 240 cps. The output is sent through series amplifier (see Chapter 11) V10, and on out to the control-track circuits.

To obtain a 960-cps pulse (needed for the switchers and the shoe servo) an additional channel is provided in the tone-wheel amplifier. This starts with the 960-cps oscillator, V18. Pulses from the oscillator are clipped in V15A and used to trigger V19, a multivibrator that develops a square wave at 960 cps for use in an automatic frequency-control comparison network. One output from V19 is differentiated and used to trigger delay multivibrator V12, a circuit that inserts an adjustable delay (370 to 750 microseconds) in the pulse to ensure operation of the switcher and the shoe servo at the correct instant of time. Delayed pulses from this circuit then trigger width multivibrator V13 whose output is sent through driver V14 to the switchers and shoe servo. The 960-cps pulse from the driver is approximately 90 microseconds wide. As it is necessary to make sure that these pulses occur at 960 cps exactly, the square wave from V19 is sent through V20A and shaper-clamper V16, a circuit that changes the square wave into a trapezoid. The trapezoid is coupled to a phase discriminator (V21) through cathode follower V20B.

In the discriminator, the 960-cps trapezoid is compared to the tone-wheel pulse obtained from V2. The pulses are first amplified in V11 to raise their level before being applied to the discriminator. The discriminator compares the two signals, and if the 960-cps signal is off frequency, it develops an error signal that is then amplified in V17 and fed back to the oscillator, V18. A switch in this portion of the circuit permits operating the oscillator with or without the automatic frequency control.

In the head-wheel servo unit the tone-wheel pulses are converted into a trapezoidal wave for use in the error-detector (see Chapter 10) circuits. Pulses from the tone-wheel amplifier are supplied, via cable, to a conventional voltage amplifier, V7A. The output of this stage is differentiated, producing a pair of sharp spikes, one positive, one negative, for each input pulse. Clipper V8A eliminates the positive spikes, while the negative spikes, corresponding in time to the leading edge of the original pulse from the tone-wheel amplifier, trigger monostable multivibrator V12, whose output is a square wave, adjustable with the control shown. The reason for this circuit is discussed below. Two output connections are provided in V12, one to the velocity error detector, the other, through cathode follower V7B, to diode trapezoid generator V9. These two tubes operate in conjunction with one another. Cathode follower V7B is biased in such a manner that negative half cycles of its input square wave render it nonconductive, while V9 then passes current. When the input to V7B reverses itself, that stage conducts, but V9 is cut off. An R-C network whose time constant is altered by the action of V9 is connected in the output of the circuit. The time constant is short (15.5 microseconds) when the input to V7B is rising, i.e., at the leading edge of the input square wave, but long (1550 microseconds) when the input drops. Thus, when the square wave starts its negative half cycle the output cannot follow it directly, and it falls off gradually, resulting in the waveform illustrated, somewhat exaggerated, in the diagram. The actual period occupied by the sloping portion of the trapezoid is approximately 100 microseconds out of a total period of 4167 microseconds. It is the slope of the trapezoid that is used for measuring errors in both position and velocity of the head wheel. To isolate the following circuits, the trapezoid is sent through a pair of cathode followers, V10A and B, before going to the two error-detector circuits.

Let us now examine the phase (or positional) error detector. 60-cps pulses from the reference generator (4 volts peak-to-peak, 200 microseconds wide) are amplified in V1A, producing output pulses with a peak amplitude of about 100 volts. These are clipped in V1B to ensure that they are uniform in height and flat topped. Noise impulses are also removed by an additional diode clipper (not shown) in this circuit. The resulting pulses are then applied to pulse generator V2A, which is essentially a voltage amplifier with a ringing coil and crystal diode in its plate circuit. The leading edge of the input pulse to V2A cuts off the tube, causing the ringing circuit to oscillate at approximately 50 kc, starting with a positive half cycle. The crystal diode effectively damps out the oscillation after the first half cycle, so the output is a single, sharp, positive pulse

that is then amplified, clipped, and inverted in V2B, producing a negative-going rectangular pulse 10 microseconds wide and 150 volts peak-to-peak. The pulse from V2B is then transformer-coupled to the phase error detector.

The error detector is essentially the same as that used in the horizontal a-f-c system of many TV receivers. The pulses from V2B are used to sample the other input to the detector, which is the trapezoid from V10A. If the phase of the head wheel is correct, the sampling pulse should coincide with the *exact center* of the sloping edge of the trapezoid. If it does, the output error signal from the detector is a small d-c value that has no effect on head-wheel speed. For convenience, this value may be assumed to be a zero reference voltage for the servo system.

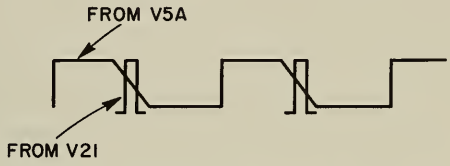


Fig. 7-8. Operation of the velocity error detector.

Suppose, however, that the head-wheel speed is altered momentarily, resulting in incorrect positioning of the heads on the track. In this instance the phase of the trapezoid will change, since it is directly related to the phase of the tone-wheel pulse which, in turn, is dependent upon the position of the heads at any given instant. Should the head-wheel position be advanced (due to a speed increase) the trapezoid phase is advanced, and the sampling pulse now appears at a lower position on the slope. This condition causes the error signal from the detector to drop somewhat, and slows the motor down until the trapezoid is again sampled at its center, once more producing a zero reference error signal. Similarly, if the head wheel loses speed, causing the head position to be retarded, the trapezoid is sampled near its positive peak, resulting in an increase in the error signal that increases the motor speed until the heads are again properly positioned. The error signal from the phase detector is now sent through cathode follower V13A which feeds it to both the velocity error detector and the motor-drive circuits.

The velocity error detector (Fig. 7-8) is similar to the phase error detector, but the error signal is developed with 240-cps sampling pulses derived from the square wave generated by multivibrator V12. The second output from V12 is differentiated and then fed through clipper V8B (to remove the positive pips) to delay multivibrator V16 where they act as triggering pulses. The delay multivibrator provides a rectangular wave that is then fed to pulse generator V18, a circuit identical to V2 except for the fact that the output sampling pulses are 20 microseconds wide and occur at a 240-cps rate. These are delivered to the velocity error detector, V17, along with the trapezoid from V10B. The error

detector operates exactly the same as V3, producing an error signal output whenever the sampling pulses are not at the exact center of the trapezoid slope. Cathode follower V13B then couples the error signal to the motor-drive circuits.

Although the velocity error detector is similar to the phase error detector, it must be modified to prevent the head-wheel motor from receiving conflicting orders when sudden changes occur. To illustrate, suppose that the head wheel is operating correctly during a recording but that the input video signal is suddenly switched to a new source with a different sync generator, causing the head wheel to appear in the wrong phase, even though its speed is correct. Such an abrupt change in the phase of the input sync to the machine, causes a time displacement of the 60-cps sampling pulses, and they no longer coincide with the center of the trapezoid. Should sampling occur, say, at the top of the slope, the error signal from the phase error detector would try to increase the motor speed for a brief interval to remove the phase difference. But as the motor speed increases, the velocity error detector would attempt to reduce the speed, thereby counteracting the needed phase correction.

To remove this conflict of orders, multivibrator V16 receives a modified signal from the phase error detector. The signal from V13A is first integrated to remove high-frequency changes, and it is then delivered to V16 through cathode follower V19A. Effectively, the signal from the phase error detector alters the pulse time of multivibrator V16 by a slight amount, so that, if a phase error is to be corrected, the velocity sampling pulse is shifted slightly along the time axis. Since the change in head-wheel speed produced by the phase correction will also alter the trapezoid period, the velocity sampling pulse now appears to again be located at the exact center of the slope (always assuming, of course, that the head-wheel speed is correct).

The 240-cps sampling pulses used in the velocity error detector do not coincide with the head-wheel position simply because they are delayed by the action of the two multivibrators (V12 and V16) in the circuit. The total time delay produced by triggering these circuits in cascade, amounts to one full revolution of the head wheel itself. Thus, the time between any sampling pulse and the leading edge of the *preceding* tone-wheel pulse is a function of the time constants of the multivibrators only, and is completely independent of head-wheel speed. Multivibrator V12 is adjusted to produce an extremely symmetrical square wave, while the width of the pulses from V16 are set so that their trailing edges coincide with the center of the trapezoid slope when the motor speed is correct. With these adjustments set, any change in motor speed will cause the relative phase of the trapezoid and sampling pulses to vary slightly, so that the velocity error detector appears to be measuring the period between successive tone-wheel pulses. For example, if the motor speed decreases, the trapezoid period is lengthened somewhat, causing the sampling pulse to move up the slope, thereby generating a positive-going error signal that increases the motor speed.

Error signals from both the velocity and phase error detectors are now combined and fed into V4 where they are used to alter the amplitude of the motor-

drive voltage. V5, a bridged-T oscillator (see Chapter 10), generates a 340-cps sine wave that is sent through buffer V6, used for isolation purposes, before entering the modulator, V4. Effectively, the modulator stage has its amplification controlled by the combined error signals, so the output is a 340-cps sine wave whose amplitude varies in accordance with both positional and velocity errors in the head wheel. The signal is then amplified additionally in V11, V14, and V15. The last stage, V15, is a cathode follower with a phase-splitting network in its output circuit. Two outputs, 90° out of phase with each other are developed and sent on to the motor-drive amplifiers. A quadrature control assures perfect 90° displacement.

The Control Track

In both the RCA and the Ampex recorders, the control track appears at the bottom edge of the tape as indicated previously. In each machine, a 240-cycle sine wave signal is placed on the track in the record mode. Due to the fact that the control track handles only a 240-cycle signal, it is possible to record this directly over the video signal without erasing, and without the use of bias. To establish proper synchronization between record and playback, only a single head is used for both recording and playing back the control track.

In the playback mode, the control-track head delivers its output to the capstan-servo system where it is compared to the tone-wheel signal. The resulting error signal is used to accurately control the capstan speed. To see how this is done, let us assume that for some reason the capstan speeds up slightly, at one point in the recording process. In turn, the physical wavelength of the 240-cycle control-track signal on the tape increases. In playback, then, the control-track signal could not be in step with the 240-cycle tone-wheel signal, and the error signal would be, let us say, some positive d-c value. Now, in the playback mode, the capstan is driven by an oscillator, and a positive error signal increases the oscillator frequency, speeding up the capstan to the same extent as in the record mode. If, on the other hand, the capstan had slowed up during recording, the control-track signal read out in playback would be out of step with the tone-wheel signal in the opposite direction, producing a negative-going error signal that would slow up the capstan. A manual control is incorporated into the capstan-servo circuits to adjust the capstan speed if necessary.

In addition to the 240-cps signals, a 60-cps pulse is also placed on the track. Although this is often referred to as an "edit" pulse, it is more correctly called a "field" pulse, since it serves to identify the vertical blanking interval between successive fields of the picture.

Ampex Capstan Servo

Figure 7-9 illustrates the Ampex capstan-servo system. Note that part of the circuit is contained in the *left-hand control panel*, the balance in the *capstan*

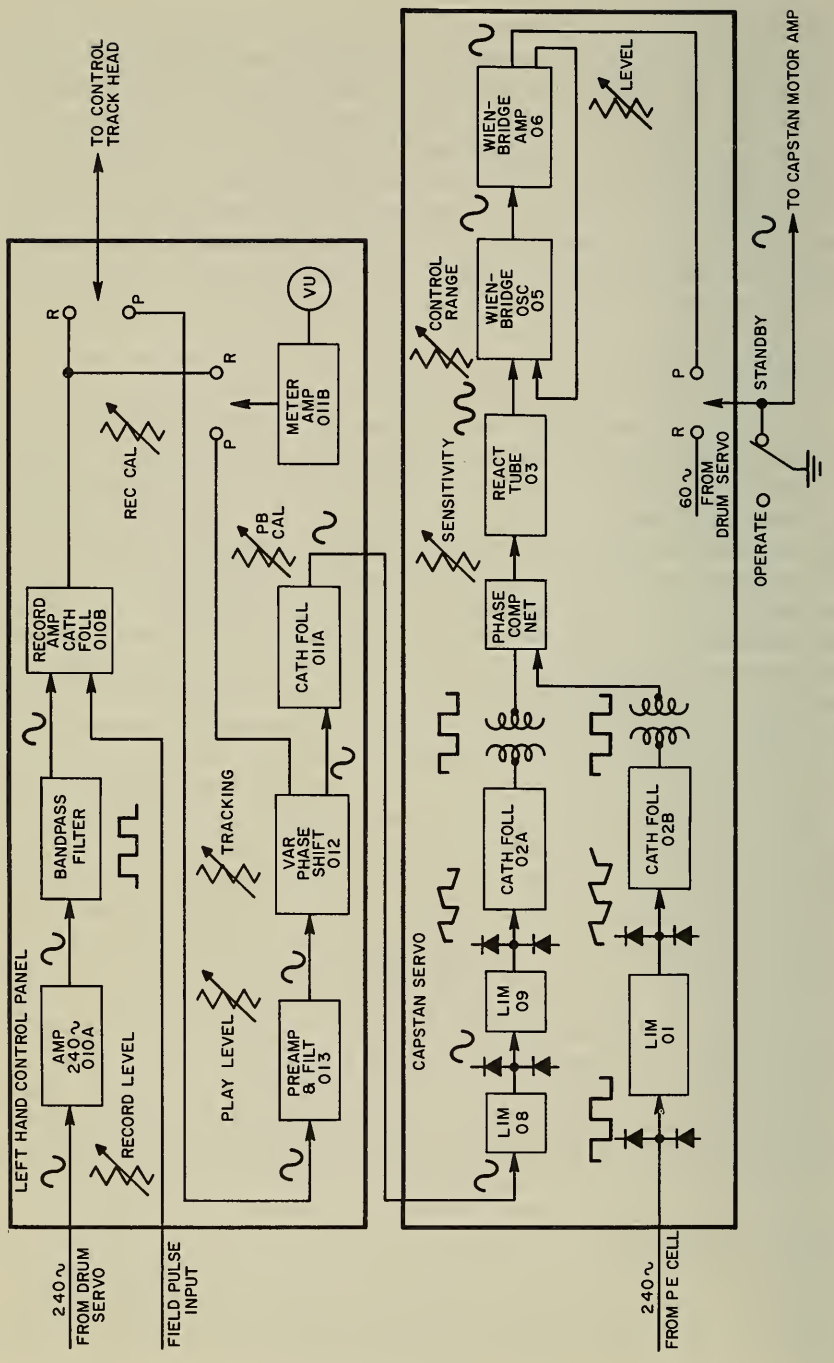


Fig. 7-9. Ampex capstan-servo system.

servo itself. The function of the entire system is to provide correct power for the capstan motor.

The 240-cps signal developed previously in the drum-servo unit, is amplified in tube 010A, filtered by the bandpass filter, and sent on to recording amplifier 010B. Due to the filter, this is a pure 240-cps sine wave signal. The "record-level" control adjusts the amplitude of the signal to be recorded. The field pulse, also manufactured in the drum-servo unit, is fed into tube 010B at the same time, and added to the 240-cps signal. This combined signal is delivered to the contacts of the record-playback relay. In the record mode, the relay sends the signal to the control-track head for recording. Simultaneously, through another set of relay contacts, meter amplifier 011B is connected to the recording amplifier for monitoring the control-track signal. A calibration control is used to set the meter level. Also, in record another record-playback relay (at the lower right) in the capstan-servo unit connects the 60-cps drive from the drum-servo unit to the output cable of the capstan servo. From here, the drive is sent to the two-phase power amplifier whose output drives the capstan. Phase splitting is done in the amplifier itself rather than in the capstan servo.

In the playback mode, the record-playback relay in the control panel connects the control-track head into preamplifier 013, and disconnects the recording circuits. The output of the preamplifier is sent to a variable phase-shifting circuit (see Chapter 10), 012. This circuit permits adjusting the capstan circuits so that the heads ride the center of the recorded video tracks. The tracking control provides any needed adjustment of head position by causing the capstan speed to change slightly. As a check on circuit operations, the signal from phase shifter 012 is delivered to the same metering circuit as was previously used for checking the control-track signal. More important, however, the output of the phase shifter is also fed to the cathode follower that sends the signal on to the capstan-servo unit. Here, the 240-cps signal is amplified and clipped by tubes 08 and 09 operating in conjunction with crystal diodes. The output of tube 09 is slightly integrated to compensate for the sloping characteristic of 02A, a transformer-coupled cathode follower. The transformer delivers the signal, a square wave, to the phase-comparison network.

In the meantime, the 240-cps signal from the photoelectric cell is amplified and clipped in the same manner as the control-track signal, by tube 01. It is fed into a similar cathode follower (02B) and transformer, and then delivered to the phase-comparison circuit. If the capstan speed is correct, the two signals appearing at the phase comparator are a quarter cycle apart in time. In this circuit the signals are fed into diodes whose outputs are equal but opposite, producing a rectangular wave. The symmetry of the wave depends upon the timing error between the two input signals. If it is not symmetrical, the output contains a d-c component whose amplitude is proportional to the error in the capstan speed. The error signal is used to control reactance tube (see Chapter 11) 03, which in turn, alters the frequency of the 60-cps Wien-bridge oscillator (see Chapter 10) 05, in order to correct the capstan speed. The output of

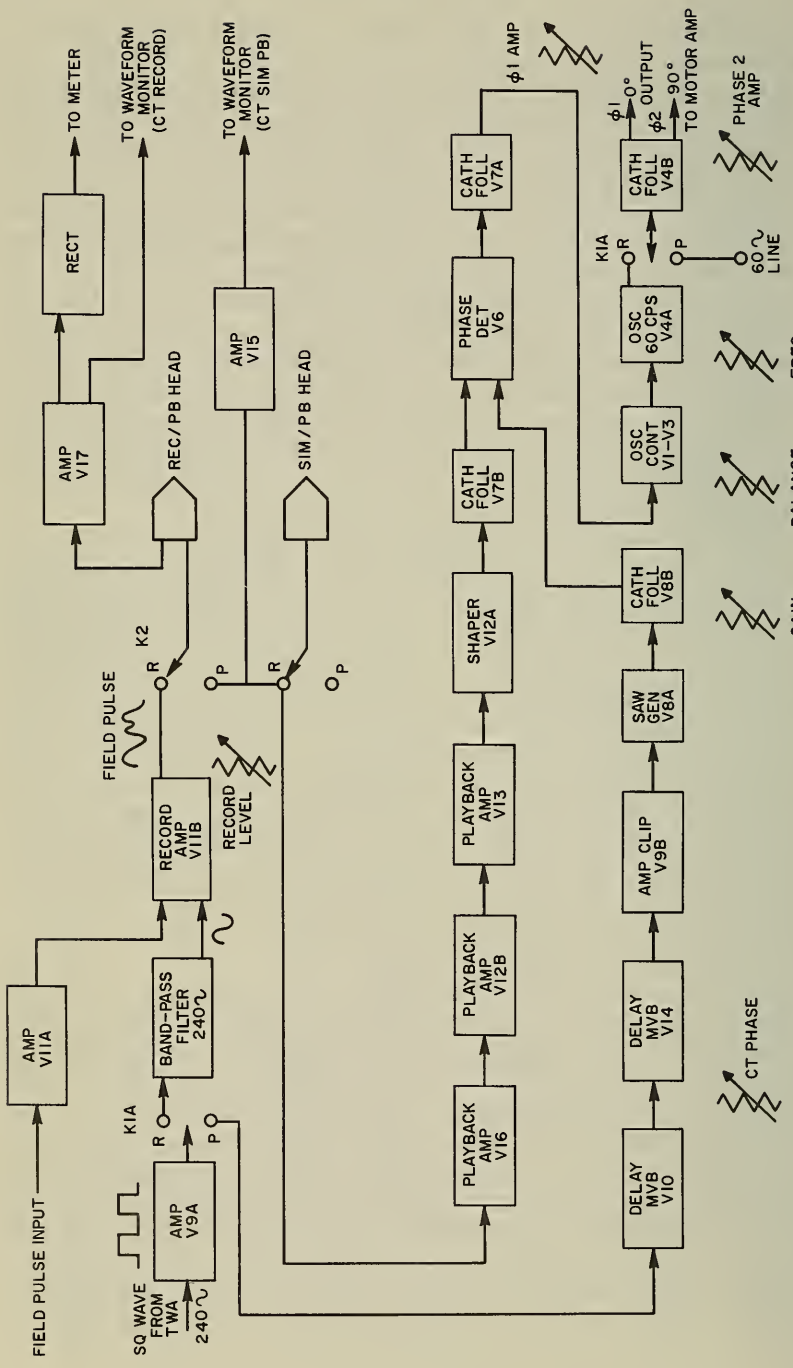


Fig. 7-10. RCA capstan-servo system.

the oscillator is amplified by tube 06 and delivered to the record-playback relay. In playback, the relay connects the output of amplifier 06 to the same phase-shift network and motor amplifiers as before. An additional relay grounds the entire system in the standby position.

RCA Capstan-Servo System

The RCA capstan servo is shown in block form in Fig. 7-10. In the record mode the capstan is driven from the 60-cps line through appropriate amplifiers. In playback, the control track is used to servo-control a 60-cps oscillator which then drives the capstan at the same speed as it achieved during recording.

In the record mode, the 240-cps square wave from the tone-wheel amplifier is fed into amplifier V9A at the top left of the diagram. The output of the amplifier is delivered to a relay-operated switch (K1A) that sends it on, through a 240-cps bandpass filter that converts it to a sine wave, to V11B, the control-track recording amplifier. Field pulses from the reference generator are also fed into the capstan-servo unit and amplified in V11A, after which they feed into V11B where they are added to the control-track recording signal. The combined signal goes through another relay-operated switch (shown in the record mode position) to the control-track record-playback head. An additional loop consisting of amplifier V17 and a rectifier is added to this circuit for monitoring purposes. Output from V17 is sent to the waveform monitor, while the rectifier feeds the control-track record current meter on the control panel. A second head on the tape deck is used as a further check. Called the *simultaneous playback head*, in the record mode it picks up the signal recorded on the control track and sends it through amplifier V15 to the waveform monitor. Push buttons in that unit permit displaying either the recording signal itself or the signal picked up by the extra head. Thus, an operator can be sure that the control track is actually being recorded properly on the tape.

In the record mode, the balance of the capstan-servo circuits are disabled. A relay (K1B) at the lower right selects 60 cps from a transformer connected to the power line, and feeds it through cathode follower V4B to a phase-splitting network. Two signals, 90° apart, are derived, and sent on to the motor amplifiers to drive the capstan. There is no servo control of the capstan in the record mode.

In the playback mode, the relays associated with the capstan servo disconnect recording amplifier V11B from the record-playback head, and connect the head instead to the servo circuits. They also reroute the 240-cps tone-wheel signal, disconnect the simultaneous playback head, and select the output from a 60-cps oscillator as the motor-drive signal. Relay K1A, in the output of amplifier V9A, feeds the square wave from the tone-wheel amplifier through a differentiator and clipper (not shown), and then into delay multivibrator V10 where negative pips from the differentiator are used as trigger pulses. The output of V10 is also passed through a differentiator and clipper, so that the trailing edge of the pulse from the multivibrator triggers the next circuit, multivibrator V14. The

length of the positive-going portion of the output from V14 is determined by the time constants of the multivibrator circuits, which are fixed, and the charge on a capacitor in each of the multivibrators (V10 and V14). The charge is adjustable with the "control-track phase" knob, located on the control panel. The range of operation of the control is wide enough to center any one of the four heads over any recorded track on the tape.

Delayed pulses from V14 are now differentiated, and the positive pips removed in the input circuits of V9B. The negative pips are inverted and ampli-

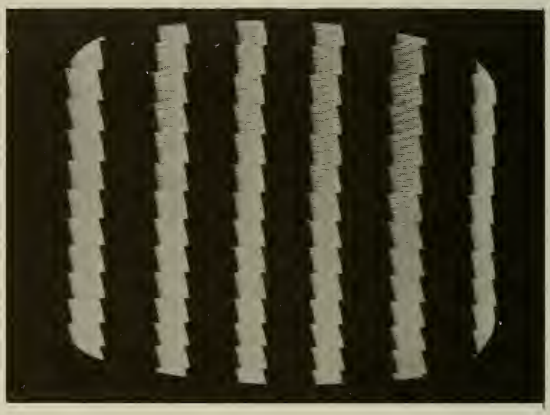


Fig. 7-11A. Venetian-blind effect on a played-back tape. Bar pattern produced by playing back correctly recorded tape on a recorder whose vacuum guide is set too close to the head. This effect is also known as skewing. *Courtesy Ampex Corp.*

fied by this stage, then clipped once more to provide flat tops, and finally applied to sawtooth generator V8A. Between pulses, a capacitor in this circuit is charged linearly. When the pulse appears, the capacitor discharges rapidly through the tube, creating the waveform indicated. This is sent through cathode follower V8B and a gain control, to the error detector.

During playback, relay K2 routes the playback signal from the control-track record-playback head through amplifiers V16, V12B and V13, in that order, to raise the signal level to an appropriate value. The playback signal is also sent through amplifier V15 to the waveform monitor. Amplifier V13, in addition to boosting the signal, serves also as a clipper, and slices off the tops of the played-back signal, converting it into an almost square waveform. This is differentiated, clipped, and applied to shaper V12A whose output is a sharp, positive spike, that is fed into driver V7B to provide sampling pulses for the error detector, V6. The detector is essentially the same as that used in the RCA head-wheel servo. Sampling should normally occur at the center of the sawtooth slope, in which case the error signal is zero. If the capstan speed is excessive, the pulses move

down the slope, generating a negative error signal that tends to reduce the capstan speed. The error signal is delivered to cathode follower V7A, and then into control amplifiers (see Chapter 10) V1 and V3.

In the playback mode, the RCA capstan motor is driven by a phase-shift oscillator (see Chapter 10) that operates at a nominal frequency of 60 cps, assuming the capstan speed is correct for the tape being replayed. When the control track indicates that a change in speed is necessary, the error signal delivered to control tubes V1 and V3 changes the frequency of the oscillator

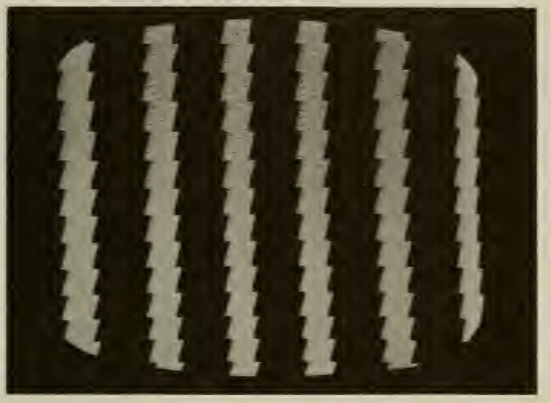


Fig. 7-11B. Pattern produced by playing back correctly recorded tape with vacuum guide set too far from head. *Courtesy Ampex Corp.*

slightly, to alter the speed of the capstan motor, which is operated synchronously Output from the oscillator is sent to relay K1B, and in the playback mode, this relay feeds the signal into cathode follower V4B and the following phase-shifting network, for delivery to the capstan motor amplifiers.

Vacuum Shoe Servo

This system adjusts the head-to-tape pressure at the rotating video heads during playback. If such an adjustment is not made, horizontal lines recorded on each track might be displaced along the time axis by a small amount, resulting in a "venetian blind" or band effect, called skewing, shown in Figs. 7-11A and 7-11B. Each small band consists of 32 to 36 interlaced lines, due to the fact that there are 16 to 18 video lines on each recorded tape track. Figure 7-11A shows the pattern produced when the tape is over-stretched; conversely, insufficient stretching results in the pattern shown in Fig. 7-11B. Errors of this type are avoided by providing correction both before and after each head switch. In the RCA machine, the circuit is known as the *shoe-position servo*; in the

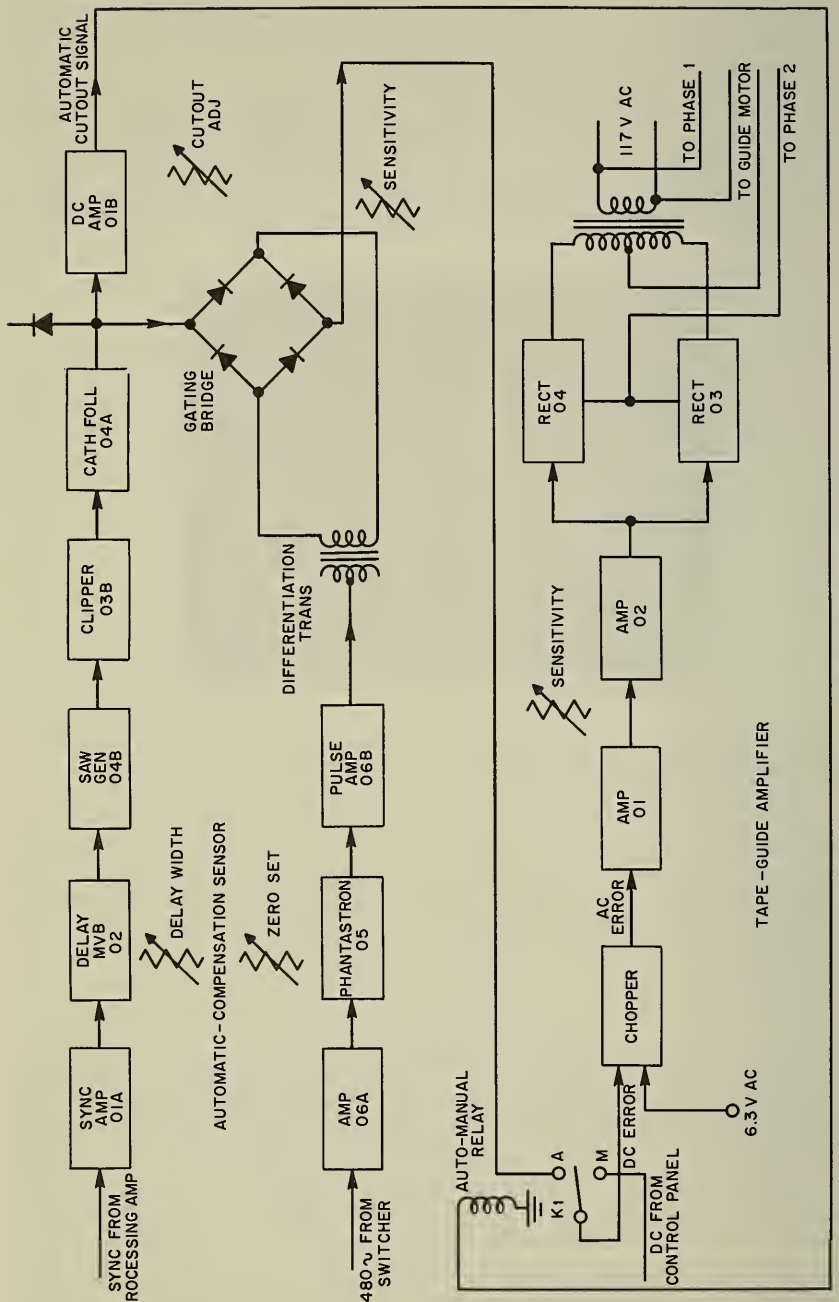


Fig. 7-12. Ampex automatic-compensation sensor.

Ampex machine it is composed of two parts, an *automatic-compensation sensor* and a *tape-guide amplifier.*

In the record mode, the tape guide is fixed in position, and provides a head-to-tape pressure in the neighborhood of 1000 lbs psi. With this large pressure acting on the tape, some slight stretching is inevitable. In playback, if the guide is

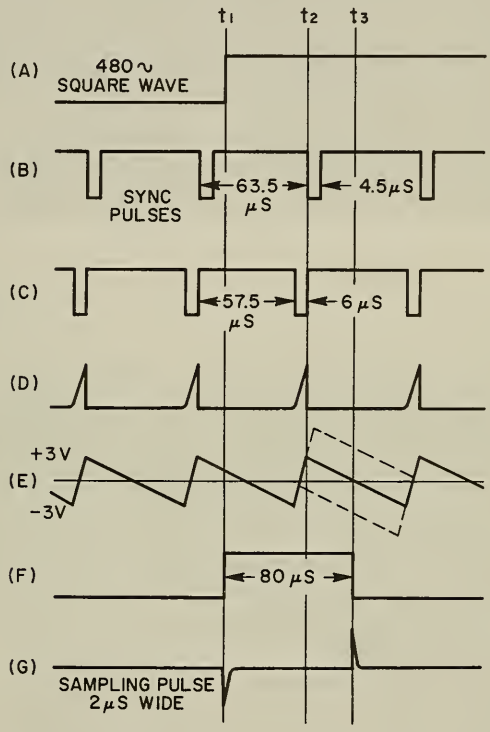


Fig. 7-13. Waveforms of the vacuum guide shown in Fig. 7-12.

moved by as much as 1 mil, the width of the tape is changed by 1.57 mils, making each horizontal video line occupy a shorter or longer portion of the tape, depending upon the direction of guide motion. Because no two machines provide exactly the same stretching of tape, the correction has to depend upon the timing of the playback horizontal sync pulses.

In the Ampex automatic-compensation sensor (shown in Fig. 7-12, with appropriate waveforms illustrated in Fig. 7-13), stripped synchronizing pulses (waveform B of Fig. 7-13) obtained from the processing amplifiers in the video circuit, are amplified, differentiated and clipped in amplifier 01A. The resulting pulses (positive only, due to the clipper), correspond to the start of each sync

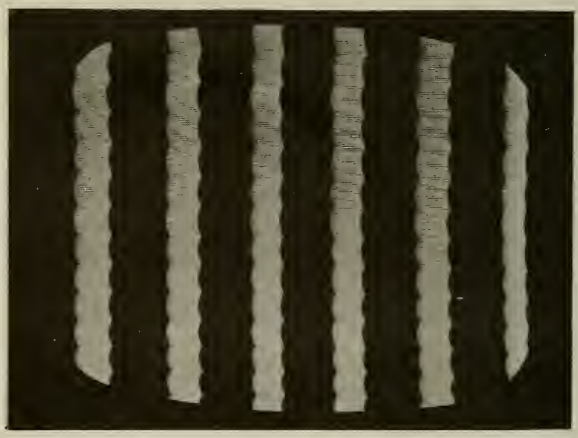


Fig. 7-14A. Incorrect vertical positioning of the vacuum guide. Pattern resulting from playing back correctly recorded tape on a machine whose vacuum guide is set too high. This effect is commonly called scalloping. *Courtesy Ampex Corp.*

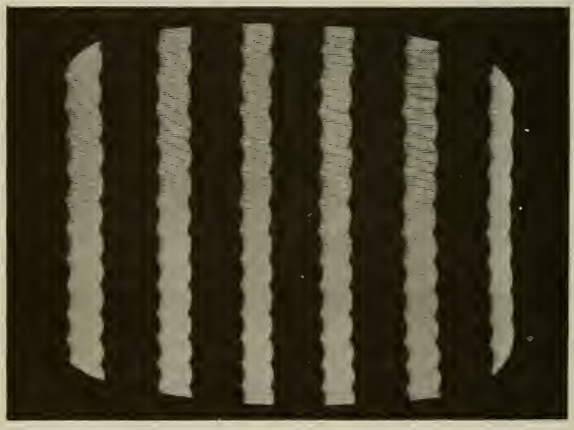


Fig. 7-14B. The result of playing back correctly recorded tape with the vacuum guide set too low. *Courtesy Ampex Corp.*

pulse, and are used to trigger multivibrator 02. This multivibrator produces positive pulses 57.5 microseconds wide, but the next sync pulse occurs in 63.5 microseconds. For this reason, the output (waveform C) appears to be a series of negative pulses approximately 6 microseconds wide, 120 volts, peak-to-peak. These pulses are delivered to sawtooth generator 04B, where they are converted into a sawtooth rising at a rate of 11.5 volts per microsecond. After 6 micro-

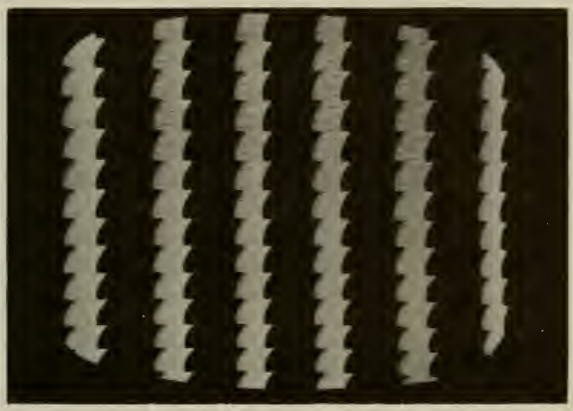


Fig. 7-14C. Result of playing back correctly recorded tape with vacuum guide set both too high and too far from the rotating head. *Courtesy Ampex Corp.*

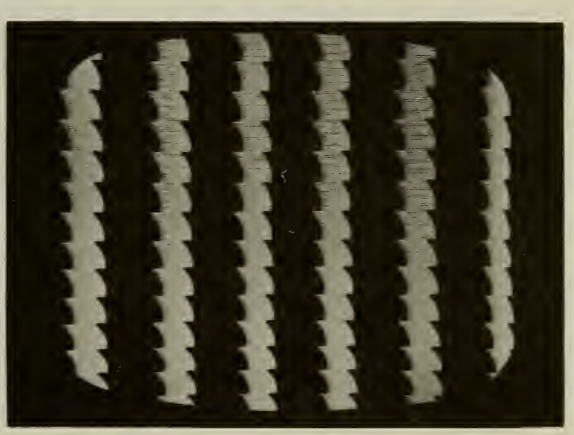


Fig. 7-14D. The result of playing back correctly recorded tape with vacuum guide set both too low and too close to the rotating head. *Courtesy Ampex Corp.*

seconds, the sawtooth is stopped, resulting in waveform D, which rises to 69 volts if the period is exactly 6 microseconds, as it will be if the guide is properly positioned.

Suppose, however, that the guide is incorrect and a timing error of 0.1 microsecond appears. Since the amount of rise of the sawtooth depends upon the time between successive pulses, the sawtooth amplitude will change accordingly, and an error of 0.1 microsecond will cause a change of roughly 1 volt in the amplitude. The output of the sawtooth is next sent to clipper 03B to remove

all but the tips of the sawtooth. A long time constant R-C network in this circuit converts the sawtooth to that of waveform E, which is delivered to cathode follower 04A, and on to a diode clipper (used to prevent noise impulses from operating the circuit). The signal is then applied to a bridge-type gating circuit (see Chapter 10) that is closed unless a switching signal is present. When the gate is opened the cathode follower output is delivered to a circuit that charges a capacitor. The amount of charge depends upon the position of the sawtooth zero axis. If the timing between sync pulses is correct, the d-c error signal developed by the charging circuit is zero. When the timing is incorrect, the error signal will be either positive or negative, depending upon the charge on the capacitor.

The circuit that opens the gate, permitting the cathode follower to deliver its signal to the output, is composed of amplifier 06A and phantastron delay circuit 05 (see Chapter 10). Tube 06A amplifies, differentiates, and clips a 480-cps signal from the video switcher. The leading edge of the differentiated wave is fed into the delay circuit of 05. The output of this circuit is a positive pulse whose width is controlled by the zero set control (waveform F). This pulse is amplified, inverted, and transformer-coupled to the gating circuit. Positive-going pulses are derived from the transformer, which differentiates the rectangular input. These pulses, 2 microseconds wide, (waveform G) are used to open the gating circuit at the correct time to accept the small signals from the cathode follower. In the event the video signal becomes very noisy, or stops completely, d-c amplifier 01B, fed from cathode follower 04A, opens the circuit of relay K1, returning the control of the tape guide to manual.

The output of the automatic sensor or, in manual control, d-c from the control panel, is next fed into a chopper (see Chapter 10), (actuated by 6.3 volts from the heater supply), producing an output square wave. The d-c error signal is thereby converted into an a-c error signal whose amplitude is dependent on the input d-c, while its instantaneous phase is determined by the polarity of the applied dc. This a-c error signal is amplified in tubes 01 and 02, and fed simultaneously to a pair of rectifiers that also receive 60 cps from the power line. The a-c error signal open-circuits the rectifiers if both halves of the error signal are *equal in amplitude and time*, thereby preventing power from being delivered to the tape-guide motor. If, however, the a-c error signal is not perfectly balanced, indicating incorrect sync timing and therefore wrong shoe positioning, one of the rectifiers will conduct more than the other, and power will be delivered to the tape-guide motor causing it to move the vacuum shoe through appropriate gearing.

The direction of rotation of the motor is determined by the current in phase 2 of the motor windings. If the current is fed to this winding through rectifier 04, the motor rotates in one direction, but if the current is sent through rectifier 03, it is of the opposite phase, and the motor rotation is reversed. When the tape-guide motor starts to rotate, of course, the sync timing starts to change. This in turn causes both the d-c and a-c error signals to change, reflecting the

new guide position. The motor continues to rotate until the sync timing is corrected, at which time the a-c error signal is again a square wave, and the rectifiers stop operating.

Although it is not corrected by the guide servo, another picture defect is traceable to the vacuum guide. If it is incorrectly positioned *vertically* during playback, the degree of tape stretching varies over the 2-inch width of the tape, producing *scalloping* effects similar to those in Figs. 7-14A through 7-14D. An

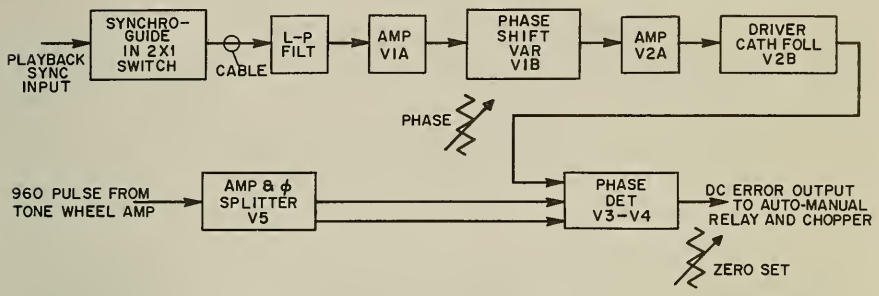


Fig. 7-15. RCA shoe servo.

adjusting screw is provided to correct for these deficiencies, and it should be checked just prior to playback.

The RCA shoe servo (Fig. 7-15) performs the same function as the Ampex system described above. Its mode of operation, however, is somewhat different. The main error-sensing device is located in the 2 × 1 switcher assembly for convenience (since it is near the reconstituted sync pulses derived from the played-back video), and is a modification of the standard synchroguide oscillator used in TV receivers. A circuit tuned to 960 cps is inserted in the synchroguide control section to detect timing variations that occur at the head switching rate. The polarity of the signal developed by the tuned circuit is dependent upon the direction of the timing error, which in turn is determined by the amount of tape stretch during playback. Output from the synchroguide is sent to the shoe-servo chassis where it is filtered to remove any 15,750-cps components. After filtering, the signal is amplified by V1A, and passed through a variable phase shifter (V1B) used to shift the signal along the time axis so that it coincides in time with the 960-cps signals from the tone-wheel amplifier. Additional amplification is provided by V2A, while V2B, a cathode follower, provides a low impedance output to a set of diode clippers (not shown). The clipped signals from this circuit then proceed to a bidirectional rectifier (a diode-bridge circuit) used as a phase detector.

A second input to the rectifier circuit is supplied by amplifier and phase splitter V5. From the tone-wheel amplifier, 960-cps pulses are fed into this stage, amplified, and split into two signals 180° apart, that are then applied to

the diode bridge to act as keyed-clamping pulses. Clamping may occur during the positive or negative portion of the signal from the synchroguide, but this depends upon the direction of the original timing error. Output from the bridge is dc, either positive or negative, again depending upon the direction of the

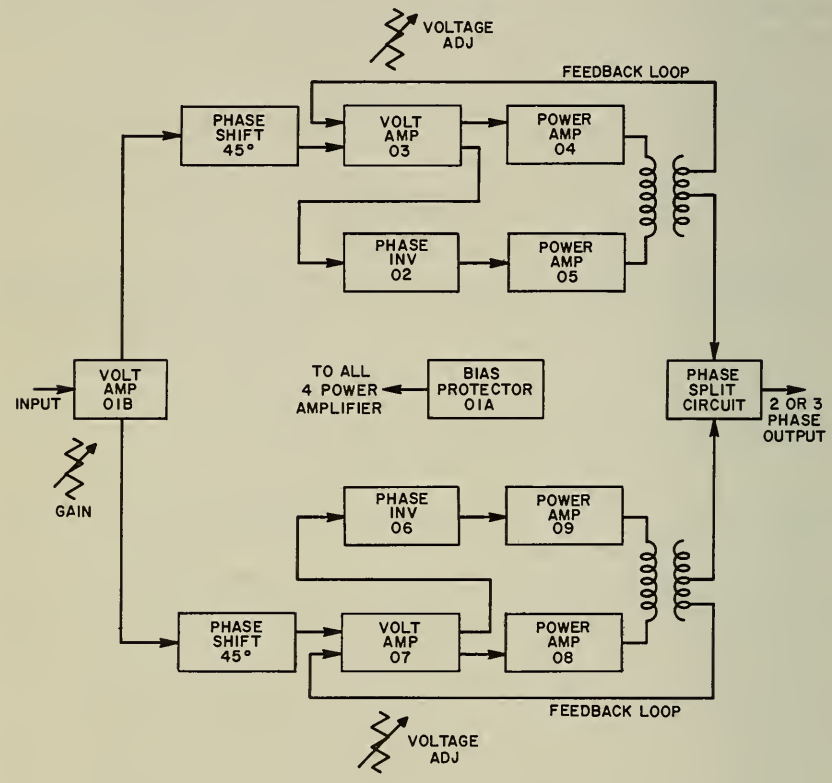


Fig. 7-16. Ampex motor amplifier.

original error. Small variations in the d-c error signal are removed by an integrating network in the bridge output; the error signal is then applied to a chopper and amplifying system similar to that used in the Ampex tape-guide amplifier. When an error in timing appears, the shoe motor is activated, and the shoe moves in or out in accordance with the error-signal directions. As the error is reduced by the shoe movement, the error signal gradually dies down, until, when the proper sync timing has been achieved, the error signal disappears.

Manual shoe positioning is provided in the RCA machine by having a relay select the input to the chopper. Dc may be substituted for the error signal, to

manually position the shoe. An additional stage, not shown, measures the amplitude of the sync pulses coming off the tape during playback, and if these drop in amplitude or disappear, the circuit energizes another relay that returns the shoe servo to manual operation if it had been in automatic. A threshold control (MANUAL SET) permits the circuit to be adjusted for any given amount of drop in sync amplitude.

Motor Amplifiers

Figures 7-16 and 7-17 illustrate the motor-amplifier circuits of both the RCA and Ampex recorders. In the Ampex machine (Fig. 7-16), two identical amplifiers are used, one for the capstan motor, the other for the head wheel. The input from the appropriate servo circuit is fed into amplifier 01B, whose output feeds two networks that create 45° phase shifts, one leading, the other lagging. The network components are adjustable to provide for 60 cps or 240 cps operation. Each network feeds into a separate, but identical, amplifier channel, culminating in a pair of output transformers. The secondaries of these transformers are tied to another phase-shifting network that may be adjusted to provide two-phase or three-phase operation, as required. A bias protection circuit (01A) prevents damage to the power amplifier during warm-up time.

In the RCA TRT-1A recorder, the capstan and head-wheel motors are driven by four identical 70-watt audio amplifiers, two for each motor. Initial phase

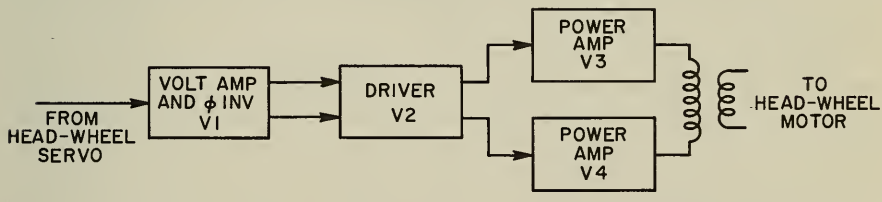


Fig. 7-17. RCA motor amplifier.

splitting is accomplished in the servo circuits, so only one phase enters each amplifier. The circuits are conventional, with V1 acting as a voltage amplifier, and V2 as the driver. The power amplifiers are connected in push-pull, and transformer-coupled to the output. For the capstan, each amplifier feeds one phase of the motor. The head wheel, however, requires three-phase operation, and accordingly the outputs of the two amplifiers are connected together in a phase-shifting arrangement that provides three outputs 120° apart.

Chapter 8

THE VIDEO SYSTEM

The Video System Simplified

Before examining the video system in detail, let us first review the major operations performed by these circuits in both the record and playback modes. Figure 8-1, a simplified diagram of the overall system, will be useful at this point. Waveforms in the various circuits are as shown.

Signals to be recorded are fed into the modulator where they are first amplified and then sent on to the modulating circuits. The modulator converts the video information into a vestigial sideband f-m signal, and supplies this to two outputs, one to the recording amplifier, the other, through a switch, to the demodulator, where it is converted back into a standard video signal for monitoring purposes. This permits checking the action of the modulator during the recording process. In the recording amplifier, the f-m signal is split into four equal signals and fed to four identical recording amplifier channels. Each channel delivers its output to the relay deck which, in the record mode, connects the outputs to the heads through the slip-ring assembly. In the RCA machine, a four-channel delay amplifier (not shown), providing individual adjustable delays for each channel, is added to the recording system to compensate for any error due to slight mislocation of the four heads on the head wheel. In the Ampex machine, tapered screws on the head wheel itself provide a somewhat similar adjustment.

In the Ampex machine the f-m signal is produced by a multivibrator modulator (see Chapter 11) when monochrome is being recorded. For color, the modulating circuits are changed to provide a sinusoidal carrier. The center frequency for monochrome is approximately 5.25 mc, but it is not maintained exactly. The modulating signal, 15 volts peak-to-peak, causes the lower-frequency deviation to reach 4.75 mc. The modulated signal is clamped to the blanking

level so that the peak of sync is held at the lower deviation limit. Because of this, the center frequency varies somewhat as the picture signal amplitude changes. The uppermost excursion of the f-m signal is 6.25 mc, corresponding

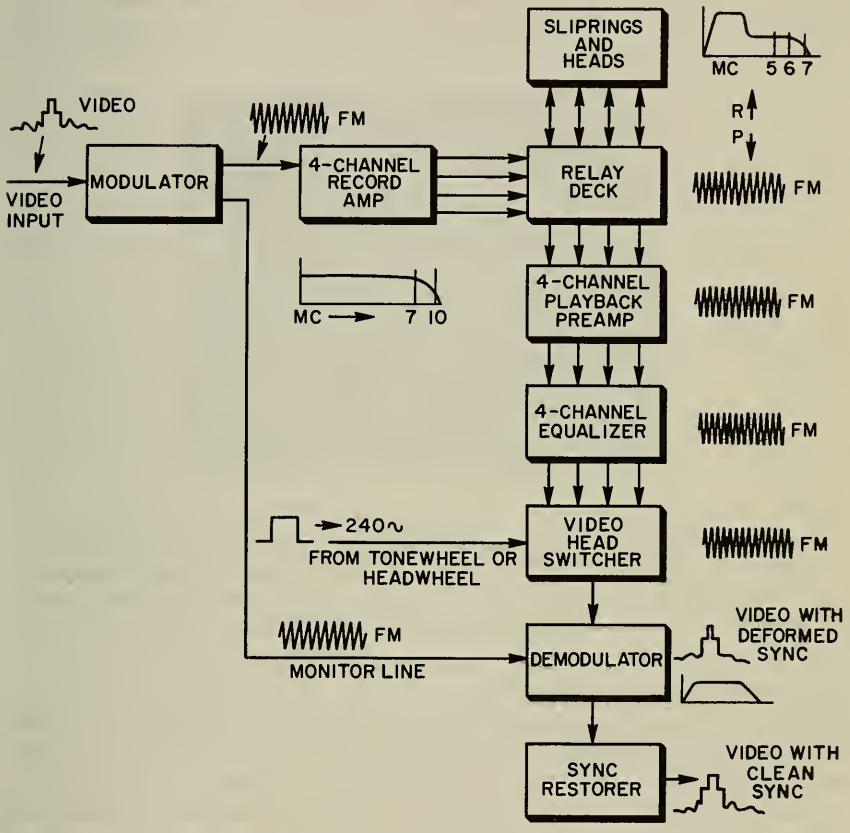


Fig. 8-1. The overall video system.

to the white level of the recording signal. For color, the frequencies are changed to coincide with those of the RCA color equipment.

The RCA recorder uses a reactance tube (see Chapter 11) modulator for both monochrome and color, providing a sinusoidal carrier in each instance. In the RCA machine the nominal center frequency is 5.7 mc, but as in the Ampex recorder, this is not fixed. Peak of sync corresponds to a peak negative deviation that reaches down to 4.3 for monochrome, but to only 5.4 mc for color. In either case, this frequency is clamped, and the center frequency therefore varies in accordance with signal amplitude. The upper deviation in the RCA machine

extends to 6.8 mc for monochrome white levels, while for color it is limited to 6.3 mc. In either machine, if the deviation exceeds the limits, the reproduced picture during playback will tend to resemble Fig. 8-2, due primarily to polarity changes in the highlight areas.

For playback, the relay deck connects the slip-ring and head assembly to the input circuits of a four-channel preamplifier. In the RCA machine, another

Fig. 8-2. High-light tearing. Polarity changes of high-light picture areas, caused by overdeviation in the modulation process. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

four-channel delay amplifier is incorporated to correct for delays in the output of any one channel. After amplification, the four-channel signals are delivered to an equalizer where additional corrections may be made. From the equalizer the signals are sent to the video head switcher, an electronic switching circuit that selects the signal from one head at a time, and removes the overlapping information on adjacent tracks without adding noise to the signal. Basically, the switcher is timed by the head-wheel or tone-wheel pulses (240 cps), although additional timing pulses are generated in both machines to trigger the switching circuits.

Although the switcher output is a continuous signal, it is still fm. Moreover, the action of the switcher tends to deform the sync pulses as well as any color burst that may be present. The demodulator removes the f-m component and sends the resulting composite video signal to the sync-restorer unit, where the old deformed sync is stripped out and replaced with reconstituted pulses, producing a final output that is a standard video signal ready for transmission. In the event a color burst is present, a color processor (not shown) takes over at this point, to make any color corrections that might be required.

The Recording Signal

The TV signal to be recorded covers a range of frequencies from 30 cps (ignoring any d-c component) to over 4 mc, providing a band in excess of 18 octaves. But, as indicated in Chapter 5, tape output during playback rises at the rate of 6 db per octave, so if the video signal were to be recorded directly, the total required dynamic range for the tape during playback would be 114 db. Such a range, however, cannot be obtained, simply because the noise level of the tape is only about 60 db less than the saturation level. If this 60-db range were used for directly recording the video signal, the low frequencies would be masked out by the tape noise (if the high end were recorded correctly), or the highs would be lost at saturation (if the low end managed to be recorded). What is more, the recording-head bias frequency would have to be in excess of 20 mc to record the high video frequencies correctly. Clearly, the video signal must be altered in some way if we expect to record it, and later play it back.

Modulated signals provide bandwidths that are usually two or more times the bandwidth of the modulating signal. Nevertheless, if the carrier is sufficiently high, the *octave range* is reduced. For example, an audio signal to be transmitted may run from 40 cps to 15 kc, a range of approximately 7½ octaves. Suppose amplitude modulation is used, with a carrier around 1000 kc. The upper and lower sidebands would extend 15 kc on either side of the carrier, producing a band of frequencies from 985 kc to 1015 kc, and we see that the bandwidth is now 30 kc, or double its former value. Considering 985 kc as the lowest frequency in the modulated signal, it is apparent that the range of frequencies is now *much less than 1 octave.* Since it is the octave range of the video signal that has created our problem, modulation may provide a solution.

Although it might be possible to use am for video recording, certain defects are evident when we examine the situation thoroughly. First, to reduce distortion to a minimum, both sidebands are needed. Additionally, the carrier frequency would have to be substantially higher than the maximum video frequency. Even if the carrier were as low as 5 mc, the upper sideband would reach 9.5 mc, requiring a further change in gap width or tape speed. For these reasons, among others, am is not used.

Frequency modulation, on the other hand, permits many improvements. First, there are no amplitude variations in the signal. The entire spectrum may therefore be recorded near saturation level, providing an improved signal-to-noise ratio. Also, since no amplitude variations are present, high-frequency bias is not needed. The only drawback to the use of fm is the custom of utilizing high carrier frequencies and high deviation ratios.

In a standard f-m signal, the maximum deviation is five times the highest modulating frequency, and the carrier is usually 1000 times greater than the modulating frequency. Under these conditions, the bulk of the energy is distributed among the first six or seven sidebands on each side of the carrier. Suppose, however, that the carrier frequency is set roughly equal to the highest

modulating frequency, and that the deviation is made quite small so that the ratio of deviation to carrier frequency is in the neighborhood of 0.1. Analysis of this type of f-m signal, with the deviation also small with respect to the highest modulating frequency, shows that the bulk of the energy is now contained in the first set of sidebands, with the second pair containing only about 3% of

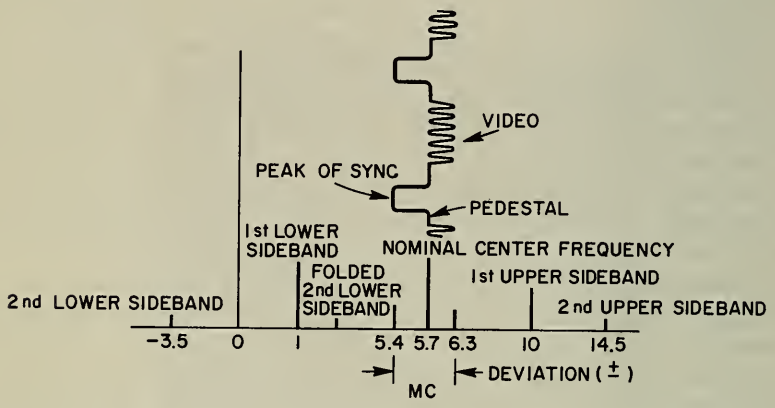


Fig. 8-3. Spectrum of the f-m signal, showing location of video signal, and sidebands for recording color. *After R. D. Thompson and M. Artzt, RCA Laboratories.*

the energy. Obviously, therefore, it is possible to use fm for the video recorder without resorting to extremely high carrier frequencies.

In an f-m signal, the instantaneous frequency is what might be called the "work-horse". It is created, though, by the sidebands. Therefore, at least all the upper, or all the lower sidebands must be transmitted, but not both complete sets. In addition, the deviation does the work of actually shifting the frequency, so both the upper and lower deviations must be included. Thus, if a carrier frequency around 5.5 mc is used, with a deviation of 500 kc, it becomes necessary to transmit the entire band of frequencies between 5 and 6 mc to cover only the deviation. As for the sidebands, since the highest video frequency to be recorded is 4.5 mc, the maximum first lower sideband extends down to 1 mc, while the corresponding upper sideband reaches 10 mc. We need use, though, only the lower sideband, as mentioned above. In this case, then, the required signal bandwidth extends from the maximum limit of the first lower sideband up to that frequency which is the sum of the carrier and the upper deviation, or, numerically, from approximately 1 to 6 mc, as indicated in Fig. 8-3. For monochrome, the deviation limits are changed as indicated previously, but in either case the required band of frequencies now covers only 2½ octaves, which greatly simplifies the playback problem.

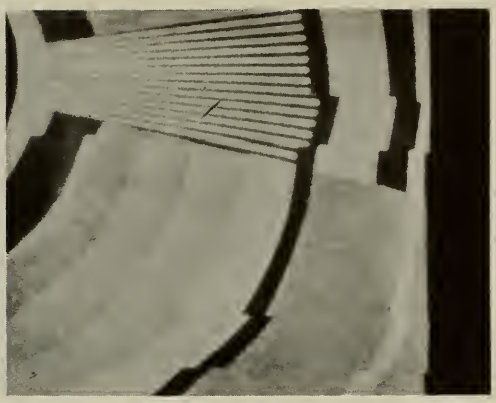


Fig. 8-4. Illustration of delay banding, made visible by difference in head geometry (quadrature), and/or by differences in electrical delay between the head channels. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

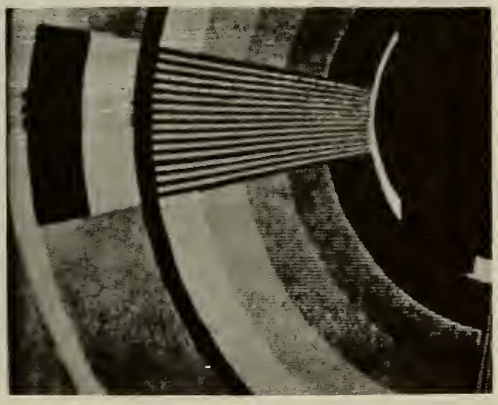


Fig. 8-5. Noise banding, made visible by differences in signal-to-noise ratios between head channels. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

An f-m signal of the type just described contains an unusual component, for the maximum second lower sideband appears to be, mathematically, a negative frequency. To the best of our knowledge, such a condition is impossible, for it is the same as permitting time to move backwards. What actually occurs is that the second sideband folds itself around the zero frequency axis and comes

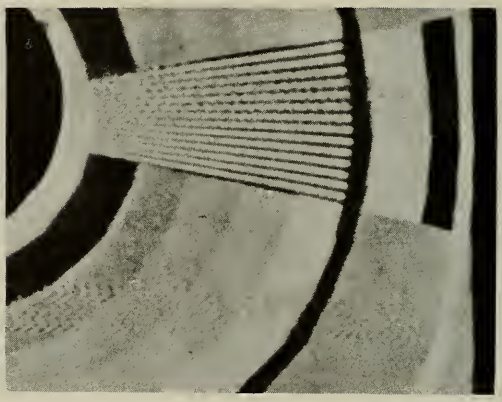


Fig. 8-6. R-f banding mode visible by undesirable r-f signals in the head channels. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

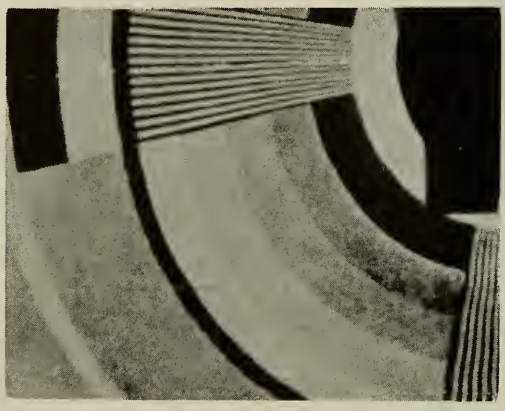


Fig. 8-7. An illustration of brush noise: A repetitive noise similar in appearance to ignition noise, caused by faulty slip-ring contact. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

back into the signal as a second-harmonic component of the modulating frequency with a reversed phase. Inasmuch as the second order sidebands are very low in amplitude, this has little effect on the overall system. If necessary, the spurious component produced by the folded second sideband may be removed with a filter.

Standard f-m signals are generally conceded to be relatively free of noise. As the ratio of deviation to modulating frequency is reduced, this noise rejection becomes poorer. In the TV tape recorder, the f-m signal is not as noise-free as a comparable a-m signal, but the use of fm solves other problems, and the resulting signal-to-noise ratio, slightly less than 40 db, is adequate for the job being done. In practice, the best overall signal-to-noise-ratio is obtained at the lower video frequencies which are more critical to the viewer. Additionally, the type of fm used in the video recorder provides some distortion of the signal by causing a zig-zag effect from line to line in a reproduced picture. This however, is averaged out by the eye of the viewer and so is not noticeable. Figures 8-4 through 8-7 illustrate some of the noises that may be seen during playback.

Video Recording Circuits

The recording circuits of both the Ampex and RCA machines contain all the circuits necessary to modulate the f-m carrier used for recording, clamp the peak of sync to the lower deviation limit, and then deliver the resulting signal to all four heads simultaneously. In the Ampex machine, four separate plug-in assemblies are used as the final recording amplifiers, one per head, while in the RCA recorder the four circuits are mounted in a single assembly. Figures 8-8 and 8-9 are the block diagrams of the RCA and Ampex recording circuits, respectively.

In the RCA machine the video signal to be recorded is fed from a standard distribution amplifier into the modulator assembly. Tubes V1 and V2 act as video amplifiers, boosting the input to a somewhat higher level. V2 is a push-pull stage; it is required to drive the filter that follows and removes any signals over 6 mc, such as noise and harmonics of the color subcarrier. Output from the filter feeds into another two-stage video amplifier (V3A and B), the second stage of which is a cathode follower used to supply two parallel outputs. If color is being recorded, a pre-emphasis network is inserted in V3A to provide a boost at the subcarrier frequency prior to recording. For monochrome, the network is short-circuited, and V3A drives V3B directly. From V3B the signals feed to both reactance tube (see Chapter 11) V6, and sync amplifier V4. The sync amplifier removes the video signal, but passes blanking and sync on to clamper (see Chapter 11) V5. It is this stage that sets the peak deviation for the sync tips.

Reactance tube V6 operates in conjunction with a standard cathode-coupled oscillator (V7) producing an f-m signal with a center frequency at about 45 mc. Some slight residual am is removed from the circuit by detuning the oscillator. The clamper (V5) is also connected to the reactance tube, causing the peak of sync to be established at approximately 46.7 mc. F-m signals from the reactance tube are now delivered to mixer V9, where they are joined by the output of master oscillator V8, operating at roughly 51 mc. Note that the difference between 51 mc and 46.7 mc is 4.3 mc, which is the deviation limit for the sync

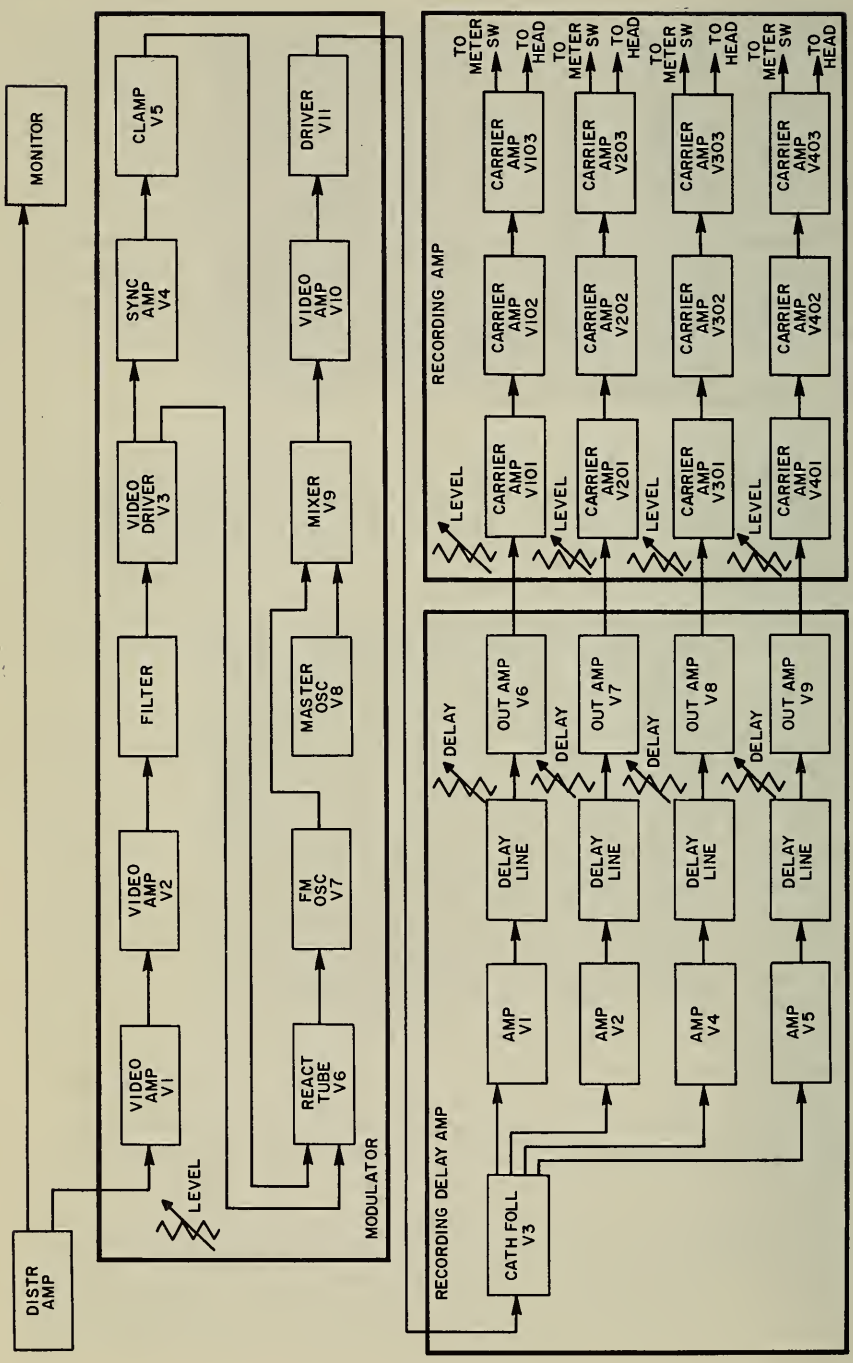


Fig. 8-8. RCA recording circuits.

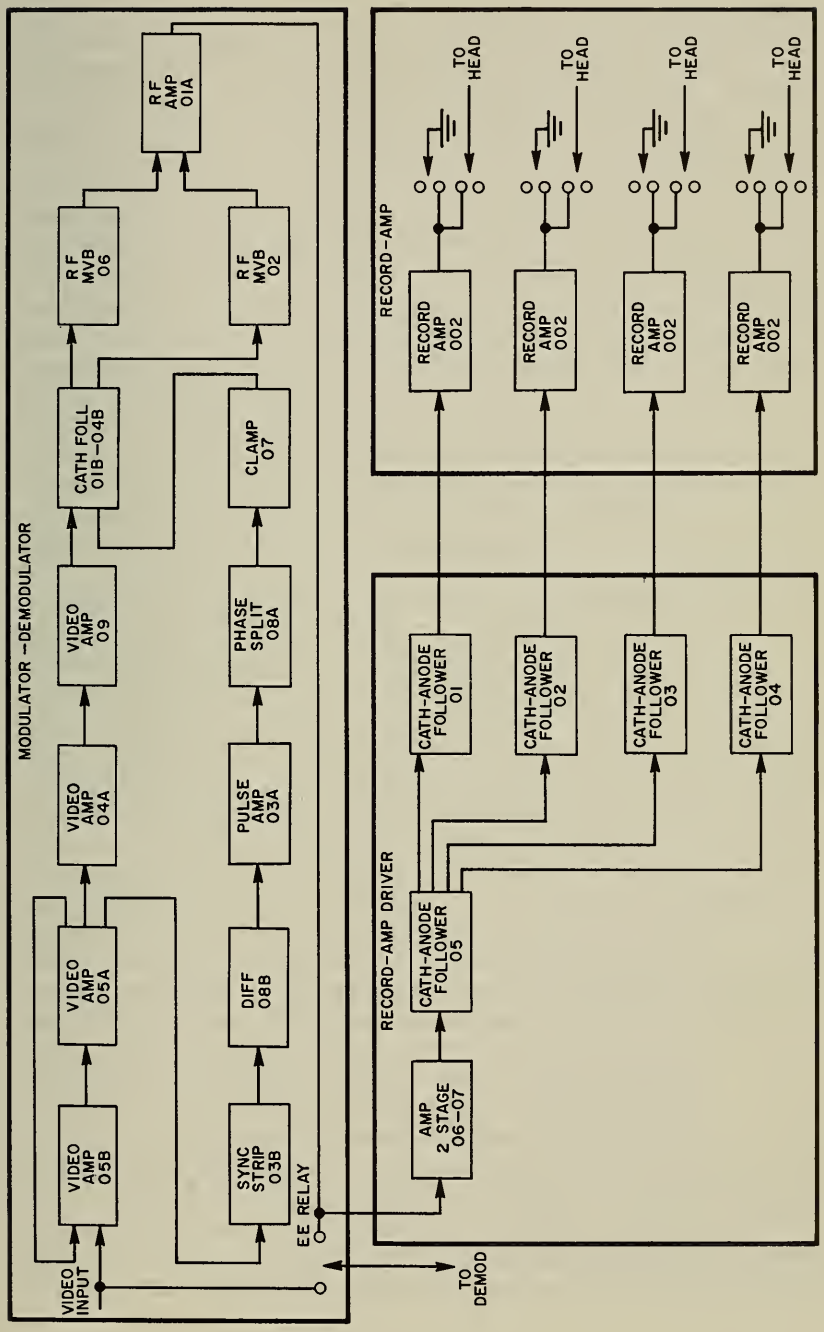


Fig. 8-9. Ampex recording circuits.

tip. The two signals are heterodyned in the mixer and the difference frequency (5.7 mc if no modulation is present), is extracted as an output. This is amplified by V10, fed into driver V11, and then through a cable to the recording-delay amplifier. Another output, not shown in the diagram, is fed back to a gating circuit that samples the driver output and activates a meter to indicate the carrier frequency.

The f-m signal entering the record-delay amplifier is first fed into V3, a cathode follower. Four parallel outputs are taken from this stage and delivered to four identical delay channels containing two amplifier stages in cascade with an adjustable delay line (see Chapter 11).

The delay line itself consists of 21 sections, each providing 0.015 microsecond of time delay. Separate and independent 20-position switches are used to select the desired delay for each channel, which may therefore be any value between 0.015 microsecond and 0.315 microsecond. The input amplifiers (V1, V2, V4 and V5), in addition to amplifying the signal, serve also to isolate the cathode-follower output connections from the delay lines, thereby reducing any possible interaction between channels. Stages V6, V7, V8, and V9 provide both amplification and proper termination for the delay lines. Additionally, they isolate the lines from the cable connections used to send the signals to the recording amplifiers.

In the recording amplifier, all channels are identical and conventional, and each contains four stages (type 6BQ7A is a dual unit). A gain control is provided in each channel for adjusting the individual recording levels for each head. Outputs are fed through cables to the playback preamplifier assembly in which the record-playback relay for the head connections is located. Another set of outputs is delivered to the metering circuits for checking head operations. From the record-playback relay, of course, the signals go directly to the slip-rings and to the heads. Although not indicated in the diagram, operating voltages for the recording and delay amplifiers are applied only in the record mode.

As Fig. 8-9 indicates, the Ampex recording circuits are located on six chassis. The modulator-demodulator assembly contains the circuits necessary for producing the f-m carrier and modulating it, while the recording-amplifier driver amplifies the f-m signal and splits it into four channels for the individual heads. Video information is fed into the first video amplifier in the modulator, 05, and on to video stages 04A and 09. Each of these is overcompensated, causing a rise in output of 12 db to appear at 4 mc as compared to the output at 0.5 mc. This corrects for a subsequent drop-off in the modulator and demodulator circuits that follow. A level control is used in the video amplifier chain to set the deviation for the f-m signal. From the video amplifiers, the signal goes to a pair of cathode followers (01B and 04B) in parallel, which are used to feed the modulator circuit itself.

The video output from amplifier 05 is also delivered to sync stripper 03B, a low-resolution amplifier. The output of this stage, mostly sync pulses, is applied to a differentiating network, and amplifier 08B. Negative pulses appearing

here are clipped so that only positive pulses arrive at pulse amplifier 03A. In addition to amplifying, this stage also clips the pulses at a predetermined level. The clipped pulses next go to phase splitter 08A and then to dual-diode clamper 07 (see Chapter 11). The pulses appearing here correspond to the trailing edge of sync. They act as keying pulses, causing the video amplitude at the grid of the cathode followers to be clamped at the level set by the carrier frequency adjustment. Regardless of video amplitude, the peak of sync is clamped to a fixed voltage.

Tubes 02 and 06 together act as an r-f multivibrator (see Chapter 11). Both are pentodes, coupled at low-voltage points, and the circuit is specially designed to prevent one tube from shorting the other. The clamped video signal from the cathode followers is coupled directly to the multivibrator so that no d-c component is lost. Now, a multivibrator will increase its frequency of oscillation if the grid voltage is increased. Since the peak of sync is negative, sync and black-level signals drive the frequency down. Conversely, white-level signals produce an increase in frequency. If no signal is applied, the multivibrator operates at 5.25 mc. Due to the nonlinear relationship between output frequency and input voltage in the multivibrator, the peak of sync reduces the frequency to 4.75 mc, while peak white increases it to 6.25 mc. R-f amplifier 01A, following the multivibrator, is used to provide the proper termination for the cable that delivers the signal to the recording-amplifier driver assembly. A separate line to the EE relay (electronics-to-electronics), feeds the modulating signal to the demodulator circuits for monitoring purposes.

In the recording-amplifier driver assembly, stages 06 and 07 are conventional pentode amplifiers incorporating a master gain control. They feed a cathode-anode follower circuit (05) (see Chapter 11) that provides a very low impedance output. This output is split into four equal channels, each having its own independent gain control for individual head adjustments. Each channel signal feeds through another cathode-anode follower circuit and on to the recording amplifiers, located in a separate assembly with the playback preamplifiers. Each recording amplifier delivers its signal to the relay that is associated with the slip-rings and heads. The recording amplifiers are conventional, and provide some pre-emphasis. A metering circuit is included in each for checking the recording-head current. As in the RCA machine, operating voltage is applied to the recording circuits only in the record mode.

Video Playback Circuits

Figures 8-10 and 8-11 are block diagrams of the video-playback amplifiers and equalizers in the Ampex and RCA machines, respectively. In the Ampex recorder, the signals from the four heads are fed into the four-channel preamplifier unit. This same assembly contains the recording amplifiers and the record-playback relay. In playback, the relay delivers the head signals to the inputs of the four separate channels. Each channel uses two cascode-amplifier (see Chap-

ter 11) stages, followed by two conventional pentode-amplifier stages. Operating voltages are applied to the preamplifier circuits only in the playback mode. When color is being reproduced, individual equalizers are switched into each channel. Output from the preamplifier is fed to the electronic head-switcher.

In the RCA recorder, a subassembly houses the record-playback relay and a single tube preamplifier for each head. The output of each of these preamplifiers

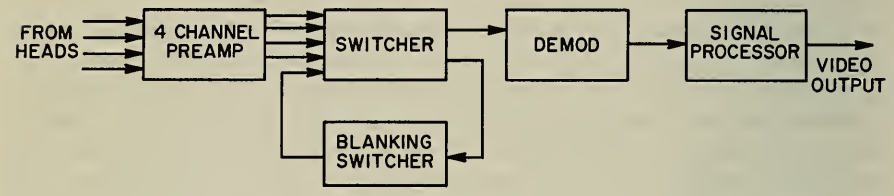


Fig. 8-10. Ampex video playback circuits.

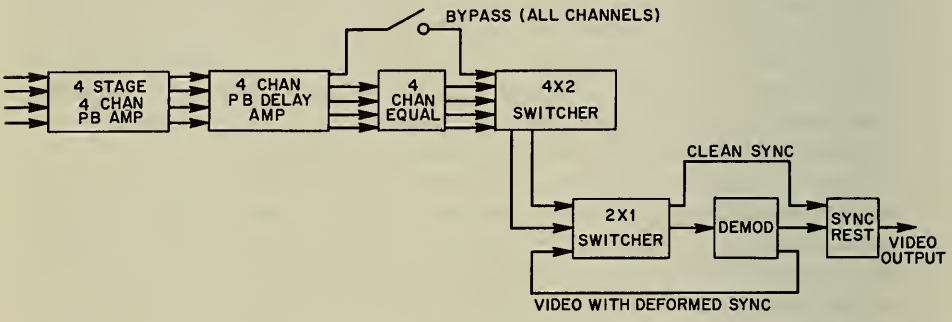


Fig. 8-11. RCA video playback circuits.

feeds a more or less conventional four-stage amplifier which includes a gain control in the 2nd and 3rd stages to set the output levels of each channel if required. The playback-delay amplifier follows the playback amplifier, and is identical to the recording-delay amplifier except that V3, the cathode follower used originally to split the recording signal into four channels, is not required. Each playback channel feeds directly into the appropriate delay channel, and any necessary delays may be inserted by adjustment of the 20-position switches. An equalizer assembly follows the playback-delay amplifier. Here too, four identical channels are used. Each equalizer channel has an independent gain control and two amplifier stages. A variable resistor is also provided to adjust the equalization in each channel. A bypass switch permits feeding the signals around the equalizer if desired. As in the Ampex machine, the outputs from the amplifiers and equalizers are sent to the switcher circuits.

Suppose we now look into the general requirements of the head-switching

circuits. First, it must be realized that it is just not possible to use mechanical switching, or commutation, to change head connections during playback, for the simple reason that switching has to occur within a very narrow interval of time. Further, any switching system, mechanical or electronic, is a noise and transient generator, and excessive noise in the reproduced picture would make the overall machine impractical. Since switching noises cannot be completely eliminated, the next best thing is to have the switching occur during an interval when it will not be noticed. Fortunately, the video signal contains such a period, the horizontal blanking interval. But this period is only about 10 microseconds in duration, so electronic switching is a necessity. It should be noted in passing, that color signals limit the switching time even more, for with color, the switch should not be allowed to take place during a color burst. Timing of the switchers is therefore locked not only to the head wheel, but also to horizontal sync. Fail-

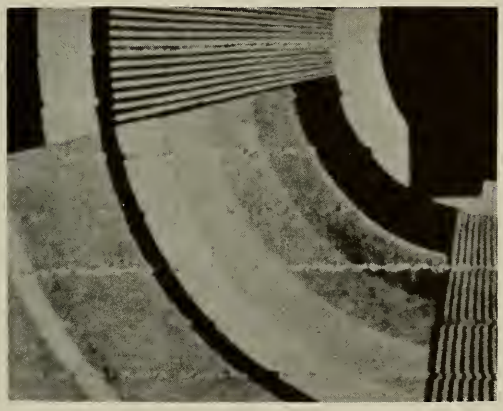


Fig. 8-12. Head-switching transients: White or black transients that occur regularly in bands, resulting from improper operation of the head-switching system. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and CBS.*

ure to provide switching during the blanking interval might result in a reproduced picture resembling that of Fig. 8-12.

Switchers should also perform two other tasks. First, the two-line overlap that exists between the bottom of one recorded video track and the top of the succeeding track, has to be removed. In practice, this is done by having the actual switch between heads occur during the horizontal blanking period following any of the last three horizontal lines on the track, as shown in Fig. 8-13. Assume the switcher operates during the blanking interval between lines 16 and 17 on the right-hand track. At this instant, head 1 is in position *A* on the

right-hand track. Thus, lines 17 and 18 on that track are not reproduced, since the switcher has disconnected head 1 from the output circuits. However, head 2 is already moving across the tape, and at the instant the switching occurs, is at position *A* on the left-hand track, so lines 1 and 2 of this track are used instead of lines 17 and 18 of the preceding track. Since lines 1 and 2 of the left-hand

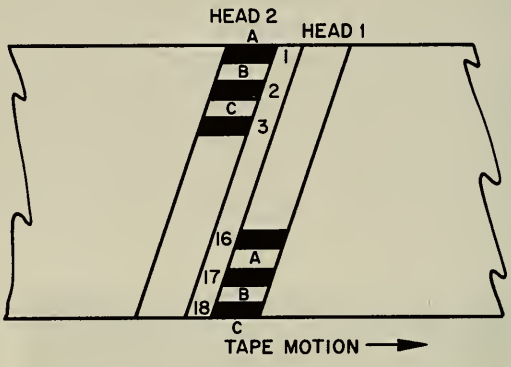


Fig. 8-13. Horizontal-line overlap on adjacent tracks.

track are duplicates of the last two lines on the right-hand track, no signal information has been lost.

Similarly, if the switching occurs between lines 17 and 18 (position *B* on track 1) line 18 is eliminated from the output signal, but simultaneously, head 2 is at position *B* on track 2, and line 2 is picked up instead of line 18. Note that in this instance, line 17 of track 1 is used instead of line 1 of track 2. Again, since the first two lines on track 2 duplicate the last two lines on track 1, no signal information has been lost. Finally, if the switcher delays its operation until the end of line 18 (position *C* on track 1), head 2 has already passed the first two lines of track 2 and is also at position *C*, ready to start the 3rd line of track 2, and once more, no signal loss occurs.

A final requirement is that the switching action be complete. By this we merely mean that any head not actually reading out information from the tape, must be completely disconnected from the demodulator circuits that follow the switcher. In this manner, noises picked up or generated by the nonreading video heads is kept out of the system.

Ampex Switcher

The Ampex switcher (Fig. 8-14) utilizes four gating circuits (see Chapter 11) acting as individual switches, with their outputs tied in parallel. These gates are driven by pulses obtained from the 240-cps head signal, since its phase is directly related to the angular position of the heads. Each circuit requires

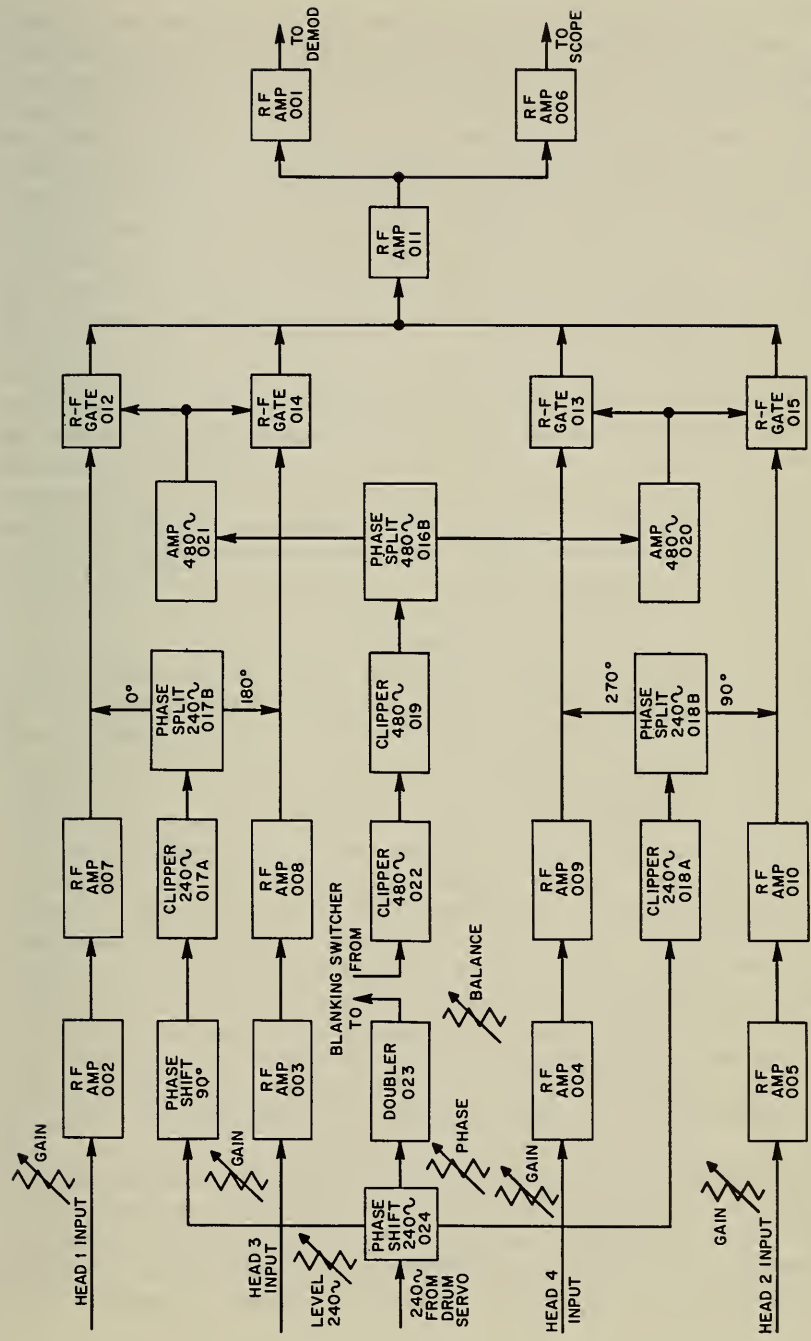


Fig. 8-14. Ampex switcher.

the presence of two pulses, a gating pulse from the 240-cps signal, and a switching pulse from a 480-cps source, generated within the switcher unit itself. The gating pulse is a trapezoid. For heads 3 and 4 it is used directly, but for heads 1 and 2 it is shifted the equivalent of 90° (one-quarter revolution of the head wheel). The gating pulses are wider in time than the switching pulses, and might be considered as "get-ready" signals that permit the gates to operate when the actual switching pulse arrives. Signals from each head (actually, from the preamplifiers) are fed into separate two-stage amplifiers. For head 1, this is composed of tubes 002 and 007. The output of 007 feeds into r-f gate 012. Identical circuits are used for each channel and, as the diagram illustrates, individual gain controls are provided for adjusting the signal levels at the gates so that they are all equal.

Let us now examine the switcher functions in detail. The 240-cps signal input is obtained from a cathode-follower circuit located in the drum-servo unit. Due to a bandpass filter preceding the cathode follower, the 240-cps input to the switcher is sinusoidal. A gain control is incorporated at the input to the switcher so that the level of this timing signal may be properly set. The 240-cps signal then feeds into tube 024, a combined cathode follower and amplifier containing a variable phase-shifting network. A control permits changing the switching time relative to the angular position of the head wheel by ± 20° from its center position. This is done to ensure switching at the proper time, since small differences exist from machine to machine.

One of the outputs from amplifier 024 is fed through an additional 90° phase-shifting network to clipper 017A. A second output feeds directly from the amplifier to clipper 018A without any phase shift. Each clipper stage is actually an amplifier associated with crystal diodes. The sinusoidal input to the stage is first amplified and then sliced off by the diodes, resulting in a trapezoid-shaped wave at the clipper output. The output of the clipper is then sent to a phase splitter (017B and 018B) so that two signals 180° apart are available from each clipper. The output of 018B provides a trapezoid that is in phase with the original 240-cps input, and another that is 180° out of phase with the original 240-cps input. Due to the 90° phase-shifter used with tube 017A, the outputs from 017B are 90° and 270° out of phase with the original 240-cps input. These four signals are the gating pulses, and they coincide with the intervals during which the successive heads are in contact with the tape. For convenience, the gating pulse used with head 1 is considered as the start of a complete cycle of head switching, and is referred to as the 0° gating pulse. The other gating pulses are labeled in accordance with their phase relationship to the 0° gating pulse.

A third output from amplifier 024 is sent to frequency-doubler 023, a double triode. The balance control ensures that both half cycles are exactly equal. Rectification is accomplished by a pair of diodes whose output is amplified in the first half of 023. Another set of diodes is used to clip the amplified output, after which the remaining signal is once again amplified in the second half of

023. A third set of diodes clips this signal once more, resulting in a square wave that is fed through a cable to a separate chassis, the *blanking switcher.*

In the blanking switcher, the square wave timing is altered slightly to coincide with the trailing edge of horizontal sync from one of the lines at the end of a recorded video track. A square wave with altered timing is then sent back to the switcher, and fed into clipper 022. A switch in the circuit permits the removal of the blanking switcher, in which case the output of doubler 023 feeds directly into clipper 022. In either event, clipper 022 receives a 480-cps square wave. Now, clipper 022 is a combination amplifier and clipper whose function is to make the square wave even more square than when it entered the circuit. The input is amplified, clipped, amplified again in the second half of tube 022, and clipped once more. The final result, a very square waveform, is then sent to 019, an amplifier containing a peaking circuit. Thus, the high-frequency components that give the square wave a fast rise time are preserved, while the wave is again clipped. The resulting output of 019 is a very square wave with an exceedingly fast rise time. It is this square wave that performs the actual switching function in the gates.

The output of clipper 019 is delivered to phase-splitter 016B to provide two out-of-phase square waves. The first of these is amplified by tube 021, the other by 020. To maintain the fast rise time of the square wave, splitter 016B and amplifiers 020 and 021 also use peaking circuits. From the amplifiers, the switching pulse is passed on to the four r-f gates.

Figure 8-15 illustrates the waveforms that appear at the gates. The vertical columns in this figure represent the periods of time during which any one head signal is read out by the switcher. The slight overflowing of the signal beyond the column edges indicates the two-line overlap for each track. Channels 1 and 3, as explained above, receive a gating pulse through phase-splitter 017B. For this reason, the two gating pulses are 180° out of phase with each other. Since the gating pulses are fed into the same point as the r-f head signals, these latter ride along on the positive-going portion of the trapezoid waves. The gates are opened, however, by the positive-going portion of the switching square wave. Thus, gate 012 (for head 1) will deliver an output signal only during the interval when the trapezoid (labeled gating 0°) and the switching 0° pulse, are both positive. At any other time, gate 012 is closed and there is no output from channel 1. Observe that the switching pulse, since it occupies less time than the incoming head signal, effectively removes the overlapping lines in the head-1 signal.

After head 1 is disconnected from the output by the end of the switching 0° pulse, the trapezoid on which the signal from head 4 is riding (gating 270°) will be positive. At the same time, due to the action of phase-splitter 016B, the 480-cps switching pulse applied to gate 013 (for head 4) will also be positive, and gate 013 will pass the head-4 signal through to the output. Since the rise time of the switching pulse is extremely fast, the output from the head-4 gate (013) follows the head-1 signal instantly, and provides a continuous signal.

At the end of the positive portion of the switching 180° pulse, which is also 180° later than the start of the head-1 signal, the trapezoid gating pulse operating with head 3 is positive, and so is the 0° switching signal. Gate 014 therefore passes the head-3 signal. Finally, at the end of the head-3 interval, the signal

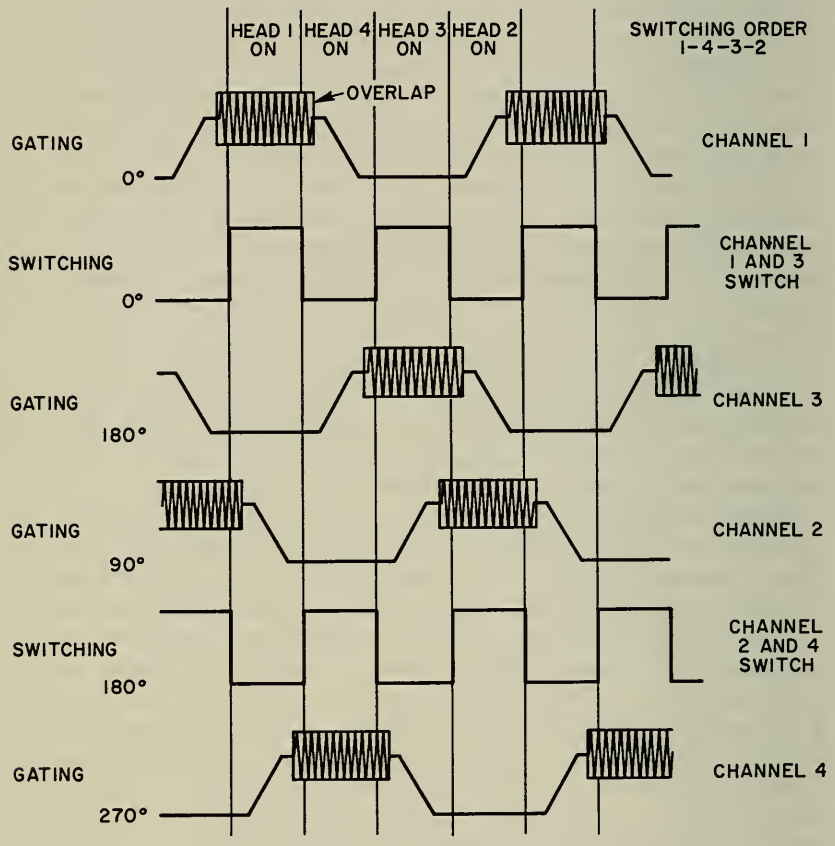


Fig. 8-15. Waveforms of the Ampex switcher.

from head 2, riding on the 90° gating trapezoid is connected to the output by its gating and switching pulses, both of which are now positive. After all four head signals have been successfully switched in this manner, the switching cycle starts all over again, and the head signals are again read out in the same order, 1, 4, 3, 2. The output from the combined gates is therefore a continuous video signal containing no overlaps, but still fm. Tubes 011 and 001 amplify this f-m signal, and send it through a cable to the demodulator. Another output, through amplifier 006, feeds the r-f signal to the waveform monitor for inspection.

Ampex Blanking Switcher

The blanking switcher, as indicated previously, is used to ensure that switching takes place during a blanking interval between adjacent lines on a recorded video track. If the blanking switcher is removed from the circuit switching will still occur, but at random times during the last three lines rather than during blanking. If the switch occurs during picture time, the switching transients that accompany the signal from the switcher will appear in the picture as noise impulses. For emergency purposes, if the blanking switcher is defective, the Ampex recorder may be played back without it.

Figure 8-16 shows the blanking switcher arrangement and waveforms. The 480-cps square wave from the frequency doubler in the switcher unit is fed into amplifier 001 (waveform *D*). This is a two-stage amplifier with a clipper between the two stages. The square-wave output of 001 is sent on to phase-splitter 002A, thereby creating two identical 480-cps square waves 180° out of phase with one another. At the same time, negative-going sync pulses developed in the processing amplifier (described later) are fed into 006 (waveform *A*). These are differentiated and inverted by 006 so that the output is a series of positive pulses corresponding to the trailing edge of each horizontal sync pulse. The pulses are used to trigger delay multivibrator 005. A bypass switch permits the removal of the delay circuit for checking purposes. In any event, the delay multivibrator operates as a free-running unit, so even if sync is not present, it still supplies the necessary waveforms to the circuits that follow.

The output of multivibrator 005 is clipped and then amplified by 004B, resulting in a series of positive-going pulses. Waveform *B* shows these pulses on a wide time base, as they compare to each horizontal sync pulse. Waveform *C* is the same as *B*, but the time scale has been altered to show the pulses with respect to the 480-cps square wave at *D*. Since the output of the trigger amplifier, 004B, it tied to the same point as the outputs of phase-splitter 002A, these spikes now ride along on both square waves, as waveforms *E* and *F* indicate. Tubes 002B and 004A are clamped clippers. Only the peaks of the spikes (above the line marked "clip level") are passed, and these are inverted in the process. The outputs of both clippers are then connected to multivibrator 003 in such a manner that it is triggered by the first negative-going spike to appear in the circuit. This causes the leading and trailing edges of the multivibrator output to be fixed in time by the first spike of each clipped wave (as indicated by the dotted line), which in turn, corresponds to the start of the back porch of horizontal blanking. The output of the multivibrator, waveform *G*, which is now not quite square because of its synchronization to the sync pulses, is then sent back to the switcher, and feeds into clipper 022 of that unit.

RCA 4 × 2 Switcher

The RCA recorder was originally designed to record and playback color sig-

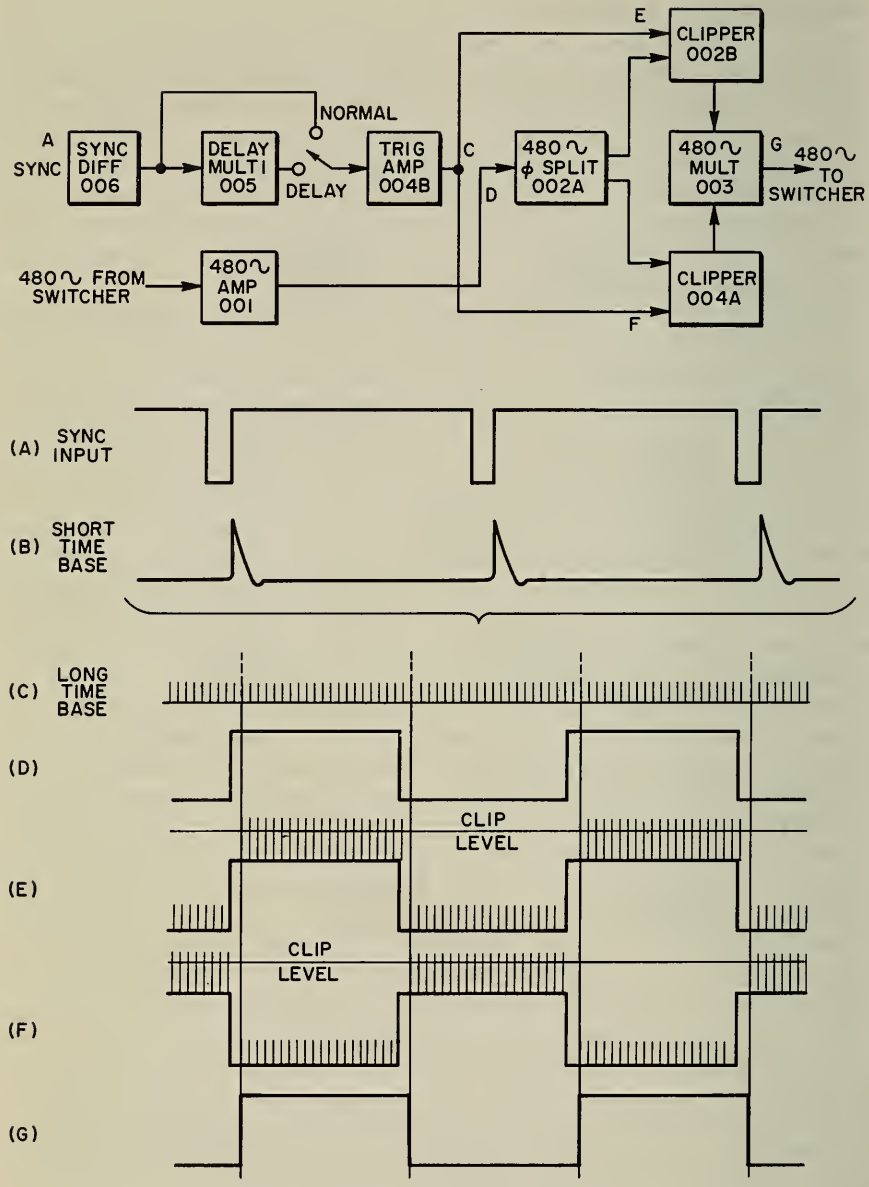


Fig. 8-16. Ampex blanking switcher.

nals, and for this reason, head switching is more closely controlled. This is done so that any color burst on the back porch, although it may be deformed somewhat, will not be removed or destroyed by the switching action. (It should be noted that in the Ampex color-conversion equipment, the switching action is also more closely controlled than in the Ampex monochrome units.) To accomplish the switch in the RCA machine, the output of the two heads that are

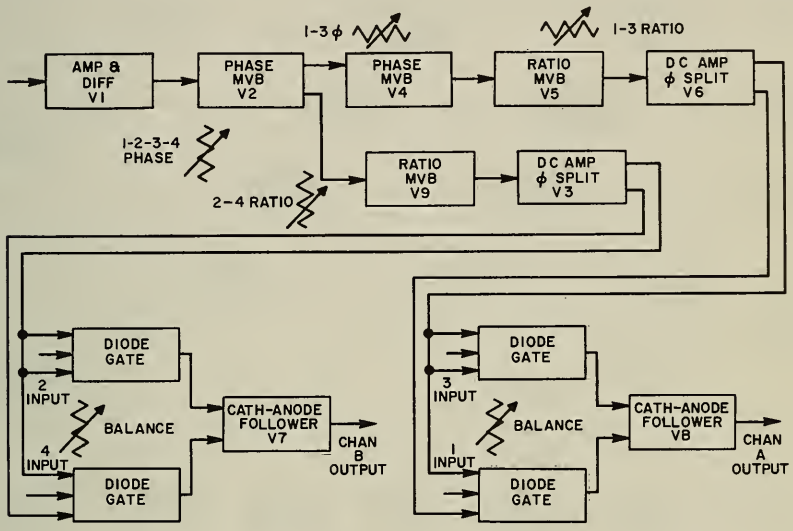


Fig. 8-17. RCA 4 × 2 switcher.

180° away from each other on the head wheel, are combined into a single signal, since at no time will they both be in contact with the tape simultaneously. The remaining two heads are also combined into a single signal. The two resulting channels are then combined into a single f-m output signal. The circuit that combines the four head signals into two outputs is called the "4 × 2" switcher, while the following circuit is known as the "2 × 1" switcher.

Figure 8-17 is a block diagram of the 4 × 2 switcher. Signals from head 1 are fed into a diode gate containing six crystal diodes (see Chapter 11). Signals from head 3 are fed to an identical circuit. These two gates are then opened and closed by a pair of switching pulses discussed below. The outputs of the gates are connected together and fed into a cathode-anode follower, V8, which delivers the composite signal (output *A* in the diagram) to the 2 × 1 switcher. The same arrangement is used for combining the outputs of heads 2 and 4, but the switching pulses are shifted along the time axis to coincide with these head signals.

A 240-cps signal from the tone-wheel amplifier is delivered to amplifier and

differentiator V1. Negative pulses from this stage are used to trigger phase multivibrator V2. An adjustment in this circuit permits setting up the proper timing for all four heads simultaneously, and is analagous to the variable phase shifter of the Ampex switcher. The output of multivibrator V2 feeds two

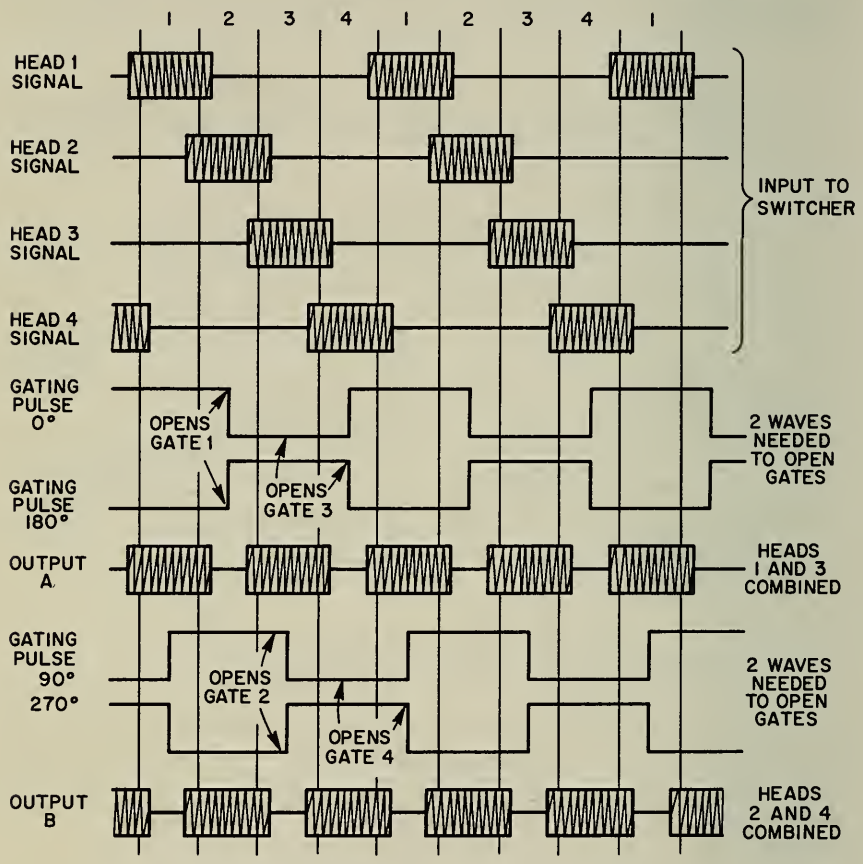


Fig. 8-18. Waveforms of the RCA 4 × 2 switcher.

circuits, one to develop the switching pulses for heads 1 and 3, the other for heads 2 and 4. The circuit used for heads 1 and 3 incorporates another phase multivibrator, V4, that delays the switching of this channel by 1045 microseconds (equivalent to one half cycle at 480 cps). Phase multivibrator V4 triggers a second multivibrator (V5) that generates the switching pulse. This is called a *ratio multivibrator* since the mark-space ratio of its output is adjustable. Multivibrator V5 operates at 480 cps, and its output is applied to d-c

amplifier and phase-splitter V6 to provide equal but opposite output signals. These are fed simultaneously to the diode gates, to which heads 1 and 3 are also connected.

The second output of multivibrator V2 is sent to ratio multivibrator V9. Since there is no additional phase multivibrator in this circuit, the output is 1045 microseconds ahead of the channel 1-3 ratio multivibrator. A control in multivibrator V9 permits adjusting the mark-space ratio as was done in multivibrator V5. Phase-splitter V3 is identical to splitter V6, but its output is sent to the gates that are used for heads 2 and 4.

The waveforms of Fig. 8-18 illustrate the action of the 4 × 2 switcher in more detail. It takes both a positive and a negative gating pulse to open the diode gates and allow the signal to pass. At the middle of the period occupied by head 2, the 0° gating pulse suddenly becomes negative, while the 180° gating pulse goes positive. This opens gate 3, as indicated, and permits the head 3 signal to pass through when it comes along. After head 3 has delivered its information, at the middle of the head 4 period, both gating pulses change polarity, the 0° pulse going positive, and the 180° pulse, negative. This opens gate 1 and permits the signal from that head, when it arrives, to pass through the gate. After this, in the middle of the head 2 period, the gating pulses again reverse themselves, once more opening gate 3. The resulting output waveform (*A*) is shown in the diagram.

The gates associated with heads 2 and 4 act in a similar manner to those described above. They are opened and closed during the head 1 and head 3 intervals by the gating 90° and gating 270° pulses, as indicated in the diagram. The output from these two combined head signals is shown at *B* in the figure. It should be noted that in the 4 × 2 switcher, no attempt to remove the overlap between adjacent head signals is made.

RCA 2 × 1 Switcher

The 2 × 1 switcher (Fig. 8-19), receives the two output signals from the 4 × 2 switcher and combines them into a single composite f-m video signal. As in the 4 × 2 switcher, diode gates are again used, but in this unit they are tube types rather than crystal diodes. In the 2 × 1 switcher the timing must be more accurate, and the switching period must be adjusted to remove the overlap that still exists in the combined signals of the *A* and *B* channels. The outputs of the diode gates are connected together and fed into a chain of f-m amplifiers, and then on to the demodulator through a cathode-anode follower circuit.

A 960-cps pulse from the tone-wheel amplifier is fed into amplifier V10, where it is amplified and differentiated. The output pulse is delivered to V9, an Eccles-Jordan binary circuit (stabilized multivibrator is another name for this circuit). The pulse acts as a reset signal for the binary, telling it to "get ready", but it does not trigger the circuit. This is done by a separate pulse derived from the video signal. Video information is fed back from the demodulator and sent

into a sync stripper circuit composed of several stages (discussed in more detail in the sync restorer section below). The stripper deletes the video information and produces output horizontal sync pulses. These are then applied to the same binary (V9) that was reset by the 960-cps pulse. The first horizontal sync pulse to arrive in the binary after it has been reset by the 960-cps pulse

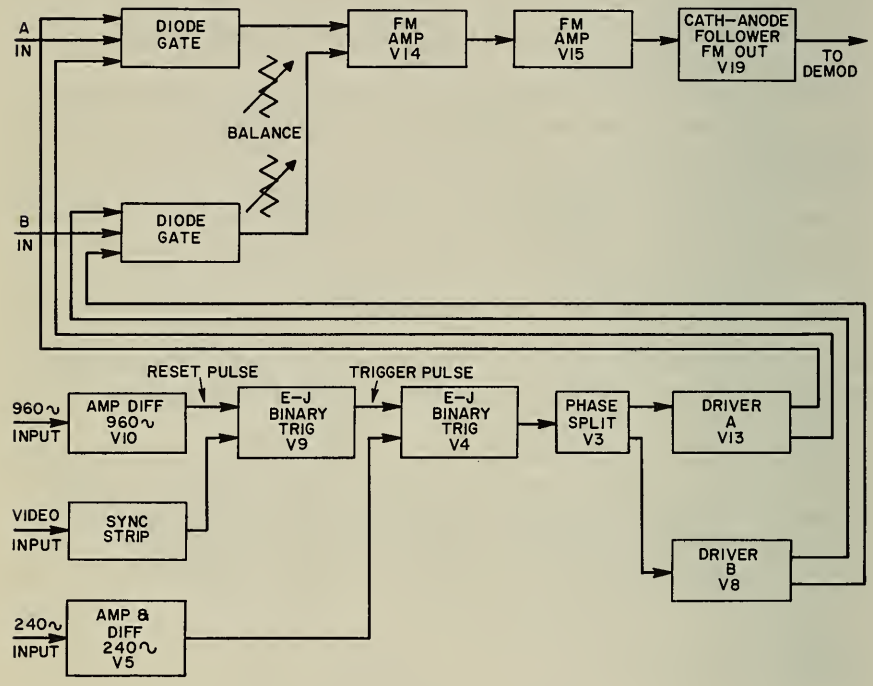


Fig. 8-19. RCA 2 × 1 switcher.

triggers the binary, causing it to deliver a pulse to the next stage. After being triggered, the binary waits for the next reset pulse before it can be triggered again. Thus, triggering occurs once for each pulse of the 960-cps signal, but at a time determined by the horizontal synchronizing pulse of the video signal.

The output pulse from binary V9 is used to trigger a second binary, V4, much the same as the first. This second binary produces a 480-cps output, roughly square, with leading and trailing edges corresponding to the timing of the sync pulses used to trigger binary V9. A second input to binary V4 delivers a 240-cps signal to the circuit to ensure proper phasing for the switching action, or in other words, to make certain that the heads are read out in the correct order. In this way, switching is ensured on one of the last three lines of any track. Due to the relative timing of the binary circuits, the switch between

heads actually occurs during the sync interval of the line being switched, rather than on the back porch. This is done to preserve the color burst if one should be present.

The output of binary V4 is fed into phase-splitter V3 and on to two separate driver stages, V8 and V13, one for each set of diode gates. The resulting output from the drivers opens and closes the gates in the same manner as in the 4 × 2 switcher, thereby providing a continuous video signal. This is sent through

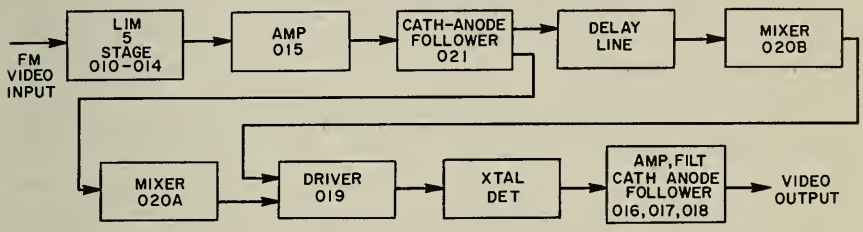


Fig. 8-20. Ampex demodulator.

V14 and V15, a pair of amplifiers, and into cathode-anode follower V19 for delivery, via cable, to the demodulator unit.

Ampex Demodulator

The demodulator circuits of both the Ampex and RCA machines remove the f-m component from the playback signal and produce an output that is essentially the same as that originally recorded. In the Ampex machine this is done by first converting the f-m signal to am and then demodulating the result. The block diagram of the Ampex demodulator is illustrated in Fig. 8-20.

One of the features of an f-m system is its relative immunity to amplitude-modulated noise. The immunity is not inherent in the signal, however. Rather, it is the fact that the information carried by the signal is in the form of frequency deviations instead of amplitude changes. For this reason, it is possible to remove any amplitude variations that exist in a received f-m signal without distorting the information. Although clippers may be used to remove any undesired a-m signals (which creep into the f-m signal from almost any kind of electrical disturbance — lightning, refrigerator motors, even the simple act of turning on a light), it is better if limiters are employed. Fundamentally, a limiter is an amplifier operated between saturation and cutoff. By proper selection of the operating voltages, these two values on the transfer curve may be made fairly close to each other. Since both ends of the curve effectively provide no amplification, only the middle, or f-m portion, of the input signal passes through such a system. To ensure good a-m rejection, several limiters are often used in cascade.

In the Ampex recorder, the signal from the switcher (or from the EE switch in the record mode), is fed into the demodulator chassis and through five limiter stages, 010 to 014 inclusive. Between 40 and 50 db of limiting is provided in this way, and practically all amplitude modulation and noise is eliminated. The output from the five cascaded limiters is amplified in 015 and sent to cathode-anode follower 021, which provides a low impedance for the following delay line (see Chapter 11). The purpose of the delay line is to provide 0.05 microsecond of delay, the equivalent of a 90° phase shift at 5 mc. For higher or lower frequencies the delay is a different value. Output from the delay line goes to mixer 20B, while an undelayed signal is sent to mixer 20A. The mixer outputs are tied together, and if the two signals from the mixers are added, the output amplitude will increase for frequencies below 5 mc, and decrease for signals above that frequency.

The change is almost linear, that is, the output voltage is practically inversely proportional to frequency. The output is therefore an a-m signal (with a little fm still remaining) but with the peak of sync appearing as the highest output voltage. This signal is next fed to driver 019, actually another cathode follower feeding a centertapped transformer connected to a crystal detector. The crystal circuit acts as a full-wave rectifier (or a-m demodulator) and provides full-time signal recovery while removing a large amount of the rf remaining in the signal. The detector output is amplified by 018 and sent through a low-pass filter which rejects frequencies above 4.5 mc, thereby removing any remaining rf. The filter also removes any second-harmonic components developed by the system. Output from the filter is amplified in 017 and delivered to cathode-anode follower 016. A cable feeds the final output to the signal-processor system.

RCA Demodulator

The demodulator system used in the RCA machine is somewhat different from the Ampex circuits, as Fig. 8-21 indicates. Basically, this demodulator, known as a *pulse-count demodulator*, is used to provide the more linear demodulation characteristic required for color signals. As with the Ampex circuits, the input to the system may be from the switcher or through the monitor selector switch.

In the RCA demodulator, tube V1 is a dual triode used for amplification and phase splitting. This is followed by push-pull stages V2 and V3, used to get the high-degree of symmetry needed for the operations that follow. A second pair of amplifiers, V4 and V5, are identical. They are followed by a pair of gated-beam clippers, V6 and V7, also operated in push-pull, that are used to slice off the peaks and make all the r-f cycles flat-topped. The clipper circuit is followed by three additional push-pull amplifiers, V8 through V13, each having a fast rise time. Stages V12 and V13 are the final amplifiers in this chain. The two outputs are then fed to V14, a dual triode. The signal from V12 is first sent through a delay line to provide 90° of shift at 6 mc before being applied to

V14A. The output of V13 is fed directly into V14B. Each section of V14 acts as a phase splitter, creating four outputs, two 180° out of phase with each other while the other two, also 180° out of phase with each other, are shifted 90° from the first pair by the action of the delay line.

Tubes V15 and V16 are both gated-beam amplifiers, requiring both inputs to be positive if an output is to result. The inputs to each are the signals that are

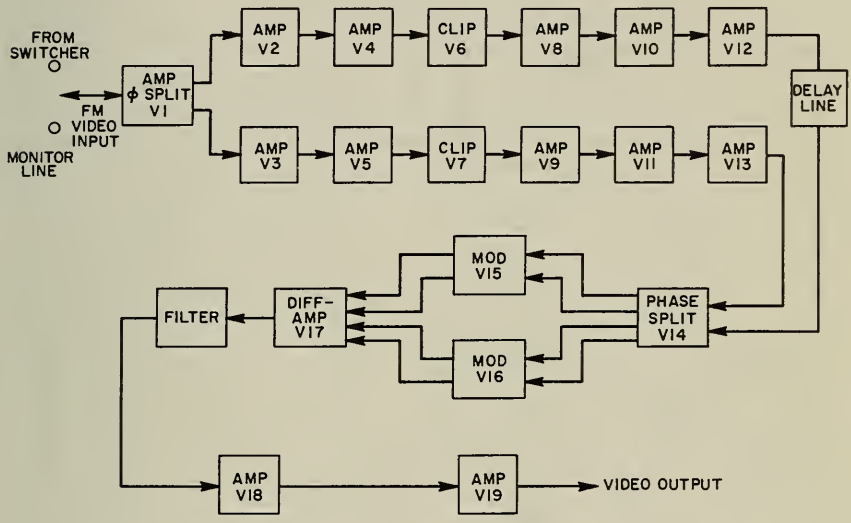


Fig. 8-21. RCA demodulator.

90° out of phase with each other. The outputs are therefore a series of pulses. Since the outputs of the two modulator stages, V15 and V16, are tied together, the pulses add to each other. The width of the output pulses is determined by the instantaneous frequency of the input. A change of frequency changes the pulse width. In turn, this changes the d-c component of the output, which is then proportional to the original video signal. The pulses therefore, by their changes, reconstruct the video signal.

The overall circuit provides a sloping transfer function for translating the fm into the required video pattern. Differential amplifier V17 is used to remove signals common to both input circuits of the modulator stages, and the following filter removes any second-harmonic components in the output. The circuit introduces a 34% drop-off in signal strength at 3.58 mc (the color subcarrier), and for this reason the modulator stages are pre-emphasized. Amplifiers V18 and V19 are conventional video amplifiers that serve to bring the signal up to the desired level before feeding it out to the sync restorer. An additional network (not shown) is inserted between amplifiers V18 and V19 to provide de-

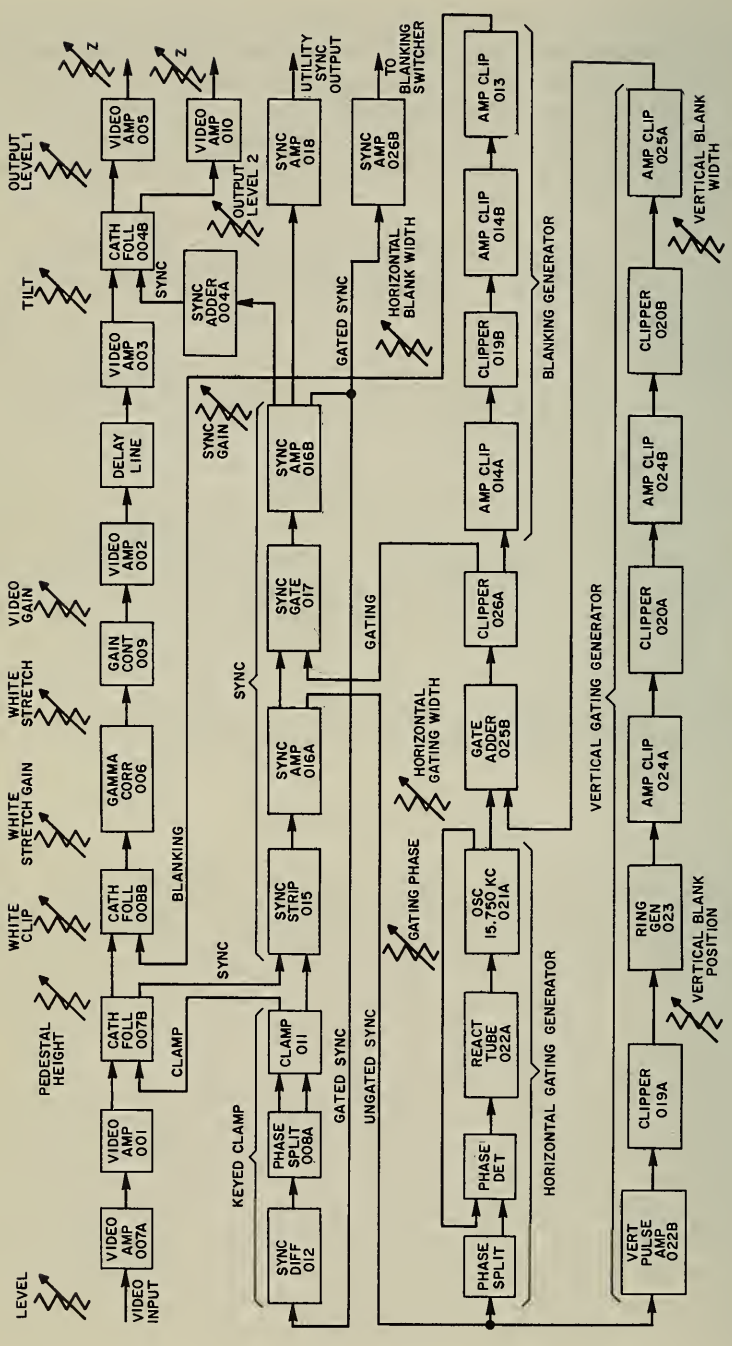


Fig. 8-22. Ampex signal processor.

emphasis when color is being played back. For monochrome, this circuit is switched out.

Ampex Signal Processor

The output of the demodulators in either machine is a standard video signal, but due to the action of the switchers, sync pulses are deformed. In addition, noise spikes appear during blanking, and these might cause difficulties at the transmitter, particularly if they exceed peak of sync in amplitude. The signal processor removes such noise pulses and reforms both the sync and blanking pulses. It also supplies gamma correction for the video portion of the signal. The resulting output is therefore a composite video signal suitable for transmission. In the Ampex signal processor, shown in block form in Fig. 8-22, four outputs are supplied, two for the video, and two for sync. The waveforms of the processor are illustrated in Figs. 8-23 and 8-24.

Video from the demodulator is amplified by 007A and 001. Also, in the output circuit of 001, a diode clips off any noise spikes larger than peak of sync. The signal is then clamped by the input circuits of 007B. This stage (007B) acts as a separator, sending the sync signals on to stripper 015, and at the same time sending the video signal (minus all sync and blanking) to 008B. A new blanking pulse, generated elsewhere, is also fed into 008B and combined with the video signal. Two controls are inserted in the circuit at this point, a pedestal-height control and a white-clip control. The former adjusts the black level and clips anything above this amount. The white-clip control adjusts the white level similarly. The result, appearing at the output of 008B, is a video signal with blanking but no sync. Furthermore, no noise exists in this signal either above blanking or below the white level.

Gamma corrector 006 follows 008B and acts as a nonlinear amplifier to compress the black level, or, conversely, to stretch the white level. Blanking is clamped to 0 volts at this point, and the stretch control then determines the peak amplitude of the white level. Gray-scale reproduction is therefore corrected in this stage. Tube 009 is used to provide for remote-control of the overall gain, and acts as an amplifier. When the remote position is used to control the machine, a relay switches out the local-gain control and substitutes the unit from a remote-control panel. Video amplifiers 002 and 003 follow the remote-gain amplifier. Delay is inserted between these two stages to allow the sync signal to catch up to the video signal in time, since a slight delay occurs in the sync-generating stages. The delay is 0.5 microsecond, a value sufficient to allow the sync signal to be properly positioned on the blanking pedestal. Clean sync is added back into the signal in the output circuit of amplifier 003, and the composite signal is then fed through cathode follower 004B into amplifiers 005 and 010 which provide the two outputs. A tilt control is used to eliminate any overcompensation in the video stages preceding amplifier 003. Sync gain (or level) is adjusted in the sync-adder stage (004A) so that the sync pulses being

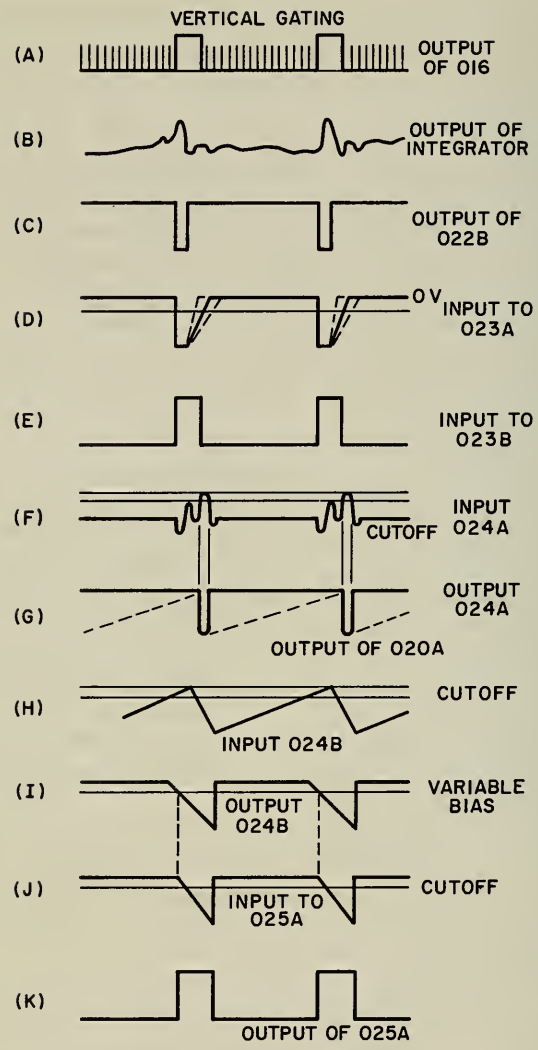


Fig. 8-23. Waveforms of the vertical circuits: Ampex signal processor.

returned to the signal are of the proper amplitude. Level- and output-impedance controls are provided for each video output.

Returning now to the sync circuits, sync signals stripped out at cathode follower 007B are clamped, amplified, inverted, and clipped, in stripper 015, amplified again in 016A, and delivered as positive-going pulses to gate 017 and both the horizontal and vertical gating circuits. A low-pass filter is placed between

stages 015 and 016 to remove any residual r-f or high-frequency noise. A pulse developed by the gating circuits is applied to sync gate 017. This pulse is just slightly wider than the sync pulse itself, so only the sync gets through the gate. Noises are eliminated by keeping the gate closed at all times except when sync is present. The gated sync is now delivered to sync amplifier 016B. From here it is sent to the sync adder and on to the two additional sync amplifiers, 018 and 026B. The sync adder, as explained above, feeds the sync back into the video signal, while amplifier 026 delivers a sync signal to the blanking switcher for use in timing the square wave of that circuit. The output of 018 is available as a utility sync signal if and when needed.

An additional output from sync amplifier 016B is used to feed back a sync signal to the keyed clamp circuit. This circuit, comprising tubes 012, 08A, and 011, develops the clamping pulse used in 07B and stripper 015. Briefly, the sync pulse delivered to 012 is widened by the addition of a quarter cycle of a 250-cps signal developed by an oscillating network in the first half of the tube. This is amplified and differentiated, so the output becomes a positive pulse corresponding to the trailing edge of sync. The action of the oscillating circuit delays this by 1 microsecond. The second half of 012 clamps the pulses, removes any negative pulses that are present, and amplifies and inverts the result, creating negative output spikes. These are split into two phases and sent on to clamper 011. The clamper operates only during the pulse interval, and since the sync was delayed by 1 microsecond, the start of the clamp period occurs during the back-porch interval. The clamp is removed from the system when the pulse input to 011 is not present.

Let us now consider the formation of the gating pulses that are used to operate sync gate 017. The output of amplifier 016A, shown as waveform *A* in Fig. 8-23, is delivered to an integrating network in the input circuits of the vertical-pulse amplifier stage, 022B, producing waveform *B*. These pulses are amplified and clamped in 022B, resulting in waveform *C*. Clipper 019A, in addition to clipping action, also provides an adjustable delay for the trailing edge of the pulse, as indicated by waveform *D*. Tube 023A is an amplifier used to invert the pulses, but it also clips them, resulting in waveform *E*. The trailing edge of this pulse now corresponds to the end of vertical blanking. These pulses are delivered to 023B, an oscillator operating at 1000 cps (1000 microseconds per cycle). The output waveform is shown at *F*. This is clipped, as indicated, in the input circuits of amplifier 024A, whose output is therefore waveform *G*. Clipper 020A contains a discharge circuit to generate a sawtooth having a fast drop corresponding to the trailing edge of blanking. This is inverted in 024B, as waveforms *H* and *I* illustrate, and clipped again in 020B. The clipping level is adjustable to set up the proper gate width. The clipped sawtooth, looking like waveform *J*, is amplified and clipped once more by 025A, producing the final output gating pulse at *K*. This is delivered to the gating adder, 025B, where it is combined with the horizontal gate.

The horizontal gate is developed by an oscillator, 021A, operating at 15,750

cps. The timing of the oscillator is controlled by the original sync signals fed through a phase splitter, phase detector, and reactance tube, to ensure proper frequency. The oscillator output is a sine wave, but by clamping at the appropriate level, the width of the resulting pulses may be adjusted, as indicated in waveform *A* of Fig. 8-24, part (A). This is added to the vertical gating pulse in adder 025B. The composite signal is then sent on to clipper 026A to shorten

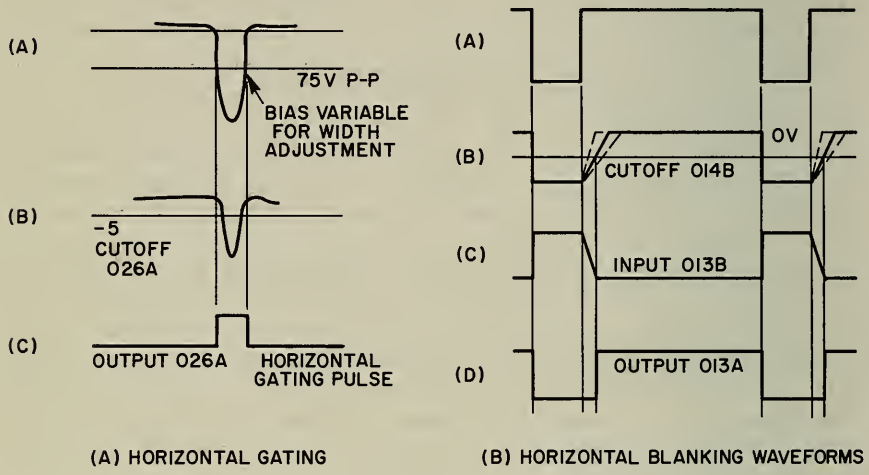


Fig. 8-24. Waveforms of the horizontal circuits: Ampex signal processor.

the pulse, as waveform *B* illustrates. The amplified output, inverted, is shown at *C*, and this, together with the vertical gate, is fed into sync gate 017.

The horizontal gating pulse from clipper 026A is also used to reform the blanking pulses. This circuit is identical to the vertical-gate circuits of 022B, 019A, and 023A, but uses stages 014A, 014B, 019B and 013B. Waveforms are as shown in Fig. 8-24, part (B). Composite horizontal and vertical pulses are fed into 014A, clipped and amplified, producing the output wave illustrated in *A*, of part (B). Clipper 014B provides a wider pulse, but one whose width is adjustable, as indicated by waveform *B*, of part (B) of the figure. After the pulses are amplified and clipped in 014B they are fed to 013B whose input is waveform *C*, part (B). Output from 013B is illustrated at *D*, part (B). This is the new blanking pulse which is sent to cathode follower 08B to be added back into the video signal.

RCA Sync Restorer

The RCA sync restorer does essentially the same job as the Ampex processor. However, a portion of the sync restorer circuits are located in the 2 × 1 switcher

unit, so that the necessary trigger pulses will be available for switching. As the block diagram, Fig. 8-25, indicates, video from the demodulator is fed into both the switcher and the sync restorer, simultaneously.

The video signal sent into the 2 × 1 switcher is amplified in V20, and clipped in V21 and V22, so that only the blanking pedestal and sync remain. At this point, horizontal sync pulses are stripped out and sent to a cathode follower and rectifier to provide bias for the shoe servo, while vertical sync is fed through cathode follower V16B into sync adder V17A along with a small portion of the blanking pedestal. Horizontal sync pulses in the output of V16B are removed and delivered to a second cathode follower, V16A, which feeds them into a phase-comparison network (not shown). The synchroguide unit indicated in the diagram (V24) is similar to that used in the horizontal circuits of many TV receivers as an oscillator, and a-f-c circuit. Fundamentally, it is a servo-controlled oscillator operating at 15,750 cps. Two outputs are available from the synchroguide circuit, a pulse output and a sinusoidal output. The sinusoidal output is delivered to delay amplifier V25, from where it is returned to the phase comparator of the synchroguide system. Here the sinusoidal output is compared to the incoming horizontal sync pulses, and if the timing is wrong, an error voltage is developed and fed to the synchroguide oscillator to correct the frequency.

The pulse output of the synchroguide (one pulse per cycle) is sent to three separate amplifiers, simultaneously. The outputs of these amplifiers feed, 1) the binary triggers of the 2 × 1 switcher; 2) the sync-restorer circuits; and 3), sync adder V17A. The adder (V17A) places the new sync pulses from the synchroguide back on the pedestal, and combines them with vertical sync. The composite signal is clipped once more in V17B, and amplified in V18 before being fed into a cable for delivery to the sync-restorer chassis.

Video signals entering the sync restorer are amplified by the first video amplifier, V1A, then delayed by 0.9 microsecond to permit sync signals from the switcher to arrive at the proper time. The video is then fed into cathode follower V1B. Output from this stage is delivered to a pair of filters that are used to separate color signals from the composite video. One filter, passing frequencies from 0-3 mc, sends sync and monochrome information through amplifier V2A, cathode follower V2B, amplifier V3, a clipper, and output amplifier V4. The second filter permits chroma signals and the color burst to bypass the sync-restorer circuits, and feeds its output to chroma amplifiers V7 and V17, after which the signal is again combined with the monochrome component to provide a composite video signal. When color is not being transmitted, the chroma channel is essentially not in use, although video components above 3 mc will still pass through it.

We must now examine the pulse circuitry of the sync restorer. Two sync signals are applied to the system, both from the 2 × 1 switcher circuits. The synchroguide pulses feed into, and trigger, multivibrator V9, which, due to its mark-space ratio, provides an appropriate delay. Output from this stage is sent

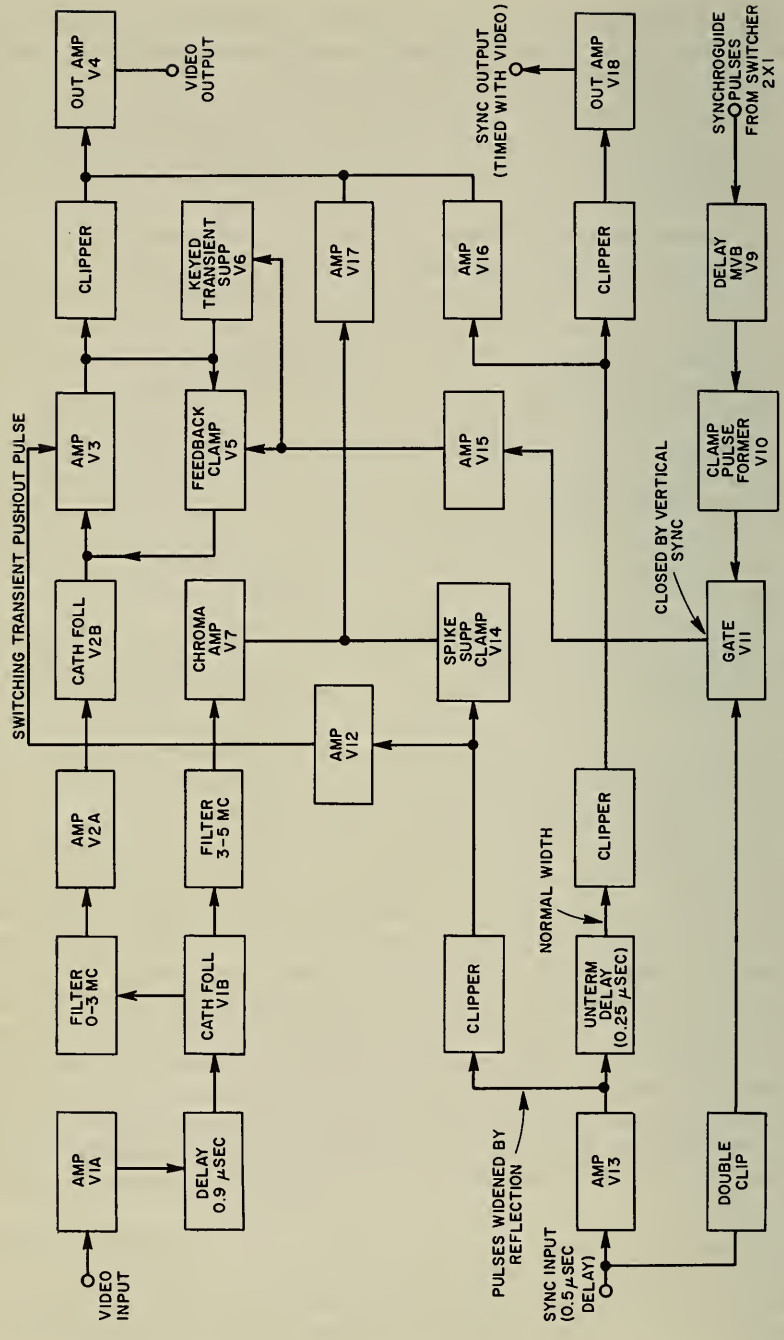


Fig. 8-25. RCA sync restorer.

to clamp-pulse former V10, a circuit that develops the pulses used to key out the old deformed sync. In turn, pulses from the former circuit are delivered to gate V11. The second sync input, delayed 0.5 microsecond, is also applied to V11, but through a clipper used to flatten the pulses. Gate V11 is open at all times except when vertical sync is present. During this interval the second sync signal (from the clipper) closes the gate. Thus, sync restoration is applied only to horizontal sync pulses. Vertical sync passing through the video chain is not affected by the restoration circuits.

The output of V11, a series of pulses coinciding with the timing of horizontal snc (but somewhat wider), is amplified by V15 and fed to clamper V5. This stage serves to remove any horizontal pulses present in the video signal passing through V3. An additional output from amplifier V13 now manufactures clean sync. This output (sync pulses of normal width) passes through a delay line to provide correct sync location on the pedestal. From the delay line the new sync is sent through a clipper to remove any possible noise and to provide a flat top, after which it goes to amplifier V16, and another clipper. The clean sync output from V16 is added directly to the chroma and burst output from V17, and the combination is then sent to V4, the output amplifier, where all signals are recombined. An additional clean sync output for use in the color circuits is provided by V18.

Finally, provision is made for removing switching transients. Another output from amplifier V13, which is somewhat wider than normal sync due to reflection from the delay line used in the clean sync channel, is clipped, and sent to amplifier V12 and spike clamper V14. The latter clamps out any transients in the chroma signal that appear during the blanking interval prior to the color burst. The pulses from V12 are fed into V3 to work in conjunction with keyed transient suppressor V6, a circuit that is actuated by the same gating pulses as clamper V5. The output of V3 therefore contains monochrome video with a blank pedestal. In order to further remove any noises not clamped out by the preceding circuits, the video signal is first passed through a clipper to obtain a flat pedestal before it is fed into V4 for its reunion with the chroma, burst, and clean sync signals.

For monochrome recordings, the output of V4 is a signal ready for transmission. For color, both the chroma and burst signals require further correction. This is accomplished with special color-correcting circuits described in the next chapter.

Chapter 9

COLOR-CORRECTION CIRCUITS

Both the Ampex and RCA video recorders provide excellent black and white reproduction, but for color, the reproduced pictures suffer from defects caused by the head wheel and the switcher. Suppose we examine these deficiencies and determine how they may be corrected.

Color Phasing

In a color signal, each horizontal video line contains, in addition to the luminance signal, a chroma signal and a color burst, both of which appear in the vicinity of 3.58 mc. At the receiver, the relative phase of the transmitted chroma signal is compared to a source of 3.58 mc, generated internally. This local signal is locked in phase and frequency to the transmitted burst. It is, therefore, the *phase difference* between the chroma signal and the color burst that determines the hue being reproduced on the screen.

Let us now study the head-wheel operation of the video recorder in detail. In the playback mode, the rotating video heads scan across the recorded tracks and read out 16 to 18 horizontal lines of video information for each traverse of a head across the tape. As the head wheel rotates, a 240-cps pulse is delivered to the head-wheel servo system to maintain correct operation. Some simple arithmetic illustrates what happens. There is only *one correcting pulse for each revolution of the head wheel*, but in the time between any two pulses, all four heads have successively scanned the tape. Thus, a correction for head-wheel speed is made only once in four head scans. Between these corrections, the head wheel may either pick up or lose speed. It is immaterial which way the head-wheel speed changes, for if it changes at all, the timing of the playback signals will be incorrect. (Slight imperfections in timing have little or no effect in

monochrome, as the eye tends to overlook them.) For color, these minute timing errors change the phase of the subcarrier and the burst during playback. Since the reproduced hue is dependent upon correct frequency and phase relationships, the result is a picture in which the hue will change in accordance with the instantaneous speed of the head wheel.

Assume for a moment, that the head wheel suffers a slight change of speed during playback. For illustrative purposes, assume also, that the head-wheel servo corrects the speed at the instant head 1 starts to read out information at the top of a recorded track. Now, as the head goes across the track, the speed of the head wheel does not change instantly to some other value. Instead, the change is gradual, and so for each horizontal line read out by the head in its passage across the tape, the *transverse head velocity is slightly different.* Inasmuch as each horizontal line occupies only 0.1 inch of tape, the change between the start of any one line and the end of the same line is relatively slight, and does not adversely affect the picture. However, the difference in head-wheel speed between successive lines gets progressively worse. If the head-wheel continues to change speed, the lines read out by heads 2, 3, and 4 will differ substantially in subcarrier phase. After the four heads have scanned the tape, the head-wheel speed is corrected by the 240-cps pulse, producing once more the correct hue. But, as the heads continue scanning, the head-wheel speed again changes, and the hues on the screen are once more altered.

The reproduced effect can best be described by considering the line-to-line action. Suppose head 1 reads out the top 16 lines of one field, head 2 the next 16 lines, head 3 the following 16, and finally, head 4 another 16. Now, at the top of the picture, the first few lines would appear normal, but as vertical scanning continues, the hues start to change. Each hue might last for several lines, then fade into some other hue. At the end of the 64th horizontal line, which is the end of the 4th head scan, the head-wheel speed is corrected by the pulse, and for a few lines the hues would again appear normal. The system would then start to drift off speed during the next 60 or so lines, more or less duplicating the results of the first 64 lines. This hue shifting continues all the way to the bottom of the raster, producing multicolored pictures in which the hues vary incorrectly from line to line. Finally, to compound the trouble, there is no guarantee that even those hues produced during any one field or frame would remain constant, for the head-wheel speed may vary in either direction, at any rate it chooses. Obviously, therefore, these hue changes must be eliminated from the reproduced picture, or patterns such as those illustrated in Figs. 9-1A through 9-1D might be obtained.

One method suggested for removing head-wheel changes requires the use of a completely different head-wheel servo system, synchronized by the 3.58 mc subcarrier itself, either from the station sync generator, or from the color burst of the incoming video. The subcarrier frequency is divided down to 240 cps to drive the head-wheel motor. A special tachometer disc, incorporating a series of black and white lines, is then attached to the motor shaft, and an optical

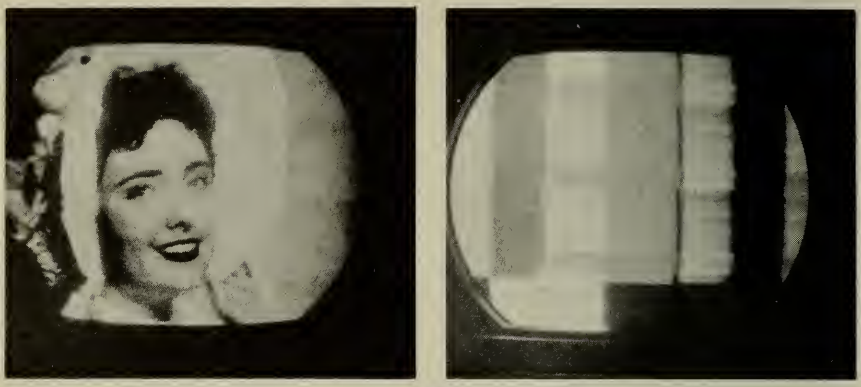


Fig. 9-1A. An illustration of color phase-shift banding made visible by differences in color phase between head channels. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and NBC.*

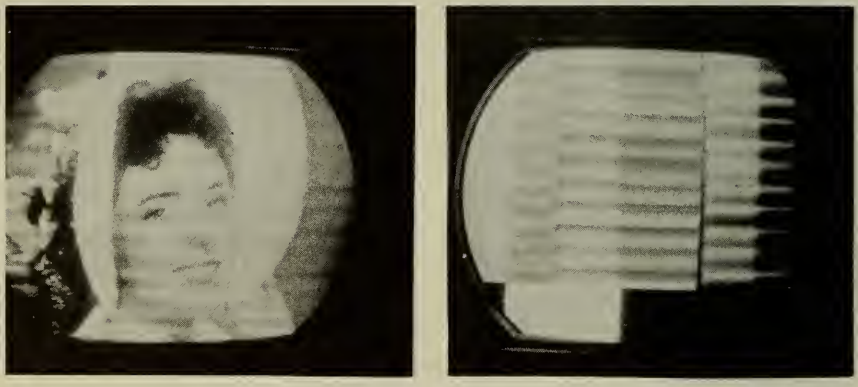
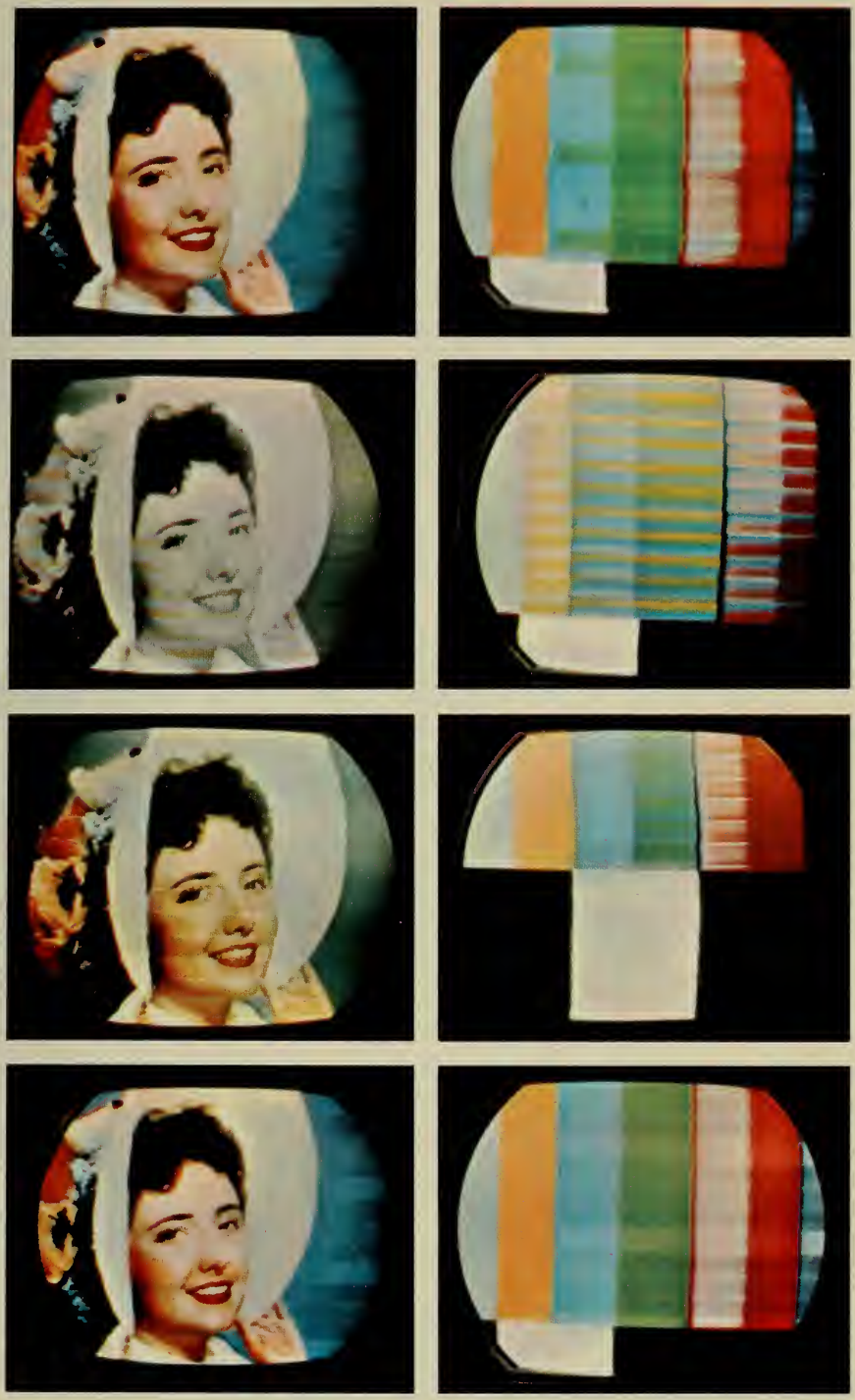


Fig. 9-1B. Hue-shift banding, made visible by hue shifts within a band. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and NBC.*

system picks up a signal from this disc. The signal is amplified and fed into a phase detector along with another signal derived from the subcarrier frequency. The resulting output of the phase detector does not correct the motor drive, but is instead applied to an eddy-current brake on the motor shaft, that either slows down the motor instantaneously, or permits it to speed up, whichever is required to maintain accurate timing. This is known as *head-drum stabilization.*



For precise interpretation, Figs. 9-1A through 9-1D are shown above in full color.

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Fig. 9-1C. First-line hue shift made visible by a difference in hue of the first line of each band. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and NBC.*

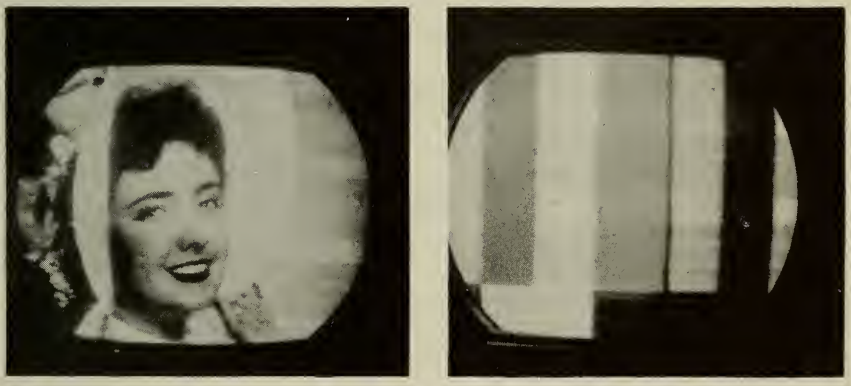


Fig. 9-1D. Saturation banding made visible by differences in saturation between head channels. *Courtesy the Network Transmission Committee of the Video Transmission Engineering Advisory Committee (Joint Committee of the Television Network Broadcasters and the Bell Telephone System) and NBC.*

Although head-drum stabilization systems provide the needed corrections, they are rather bulky mechanically, and have not been adopted for use on current machines. Rather than attempt to correct the head wheel itself, both machines utilize electronic circuits that cancel the phase errors in the output signal.

The color burst in a playback signal must also be preserved to serve as a reference for chroma information. However, the switchers may easily create

difficulties here, for depending upon just when the switching takes place, the burst may or may not be chopped up. If switching occurs during sync, or during the interval between the trailing edge of sync and the start of the burst, the chopping action does not appear, but switching transients are generated. These act as noise impulses in the burst, and may therefore cause trouble. Additionally, whenever the chroma components along any line of video information are shifted in phase, the burst itself suffers a similar shift. It seems clear that, in addition to head-wheel corrections, a burst correction is also needed. The simplest method of obtaining such a correction is to strip out the old burst and replace it with a new one. This is done in both machines.

RCA Color-Correction Circuits

Figure 9-2 illustrates, in block diagram fashion, the major components of the RCA color circuitry. The video signal from the sync restorer is fed into two components, a set of filters and a *burst-controlled oscillator.* The filters split the video signal into two bands, one extending from 0 to 3 mc (and therefore containing no color information), the other from 3 to 4 mc. This higher band

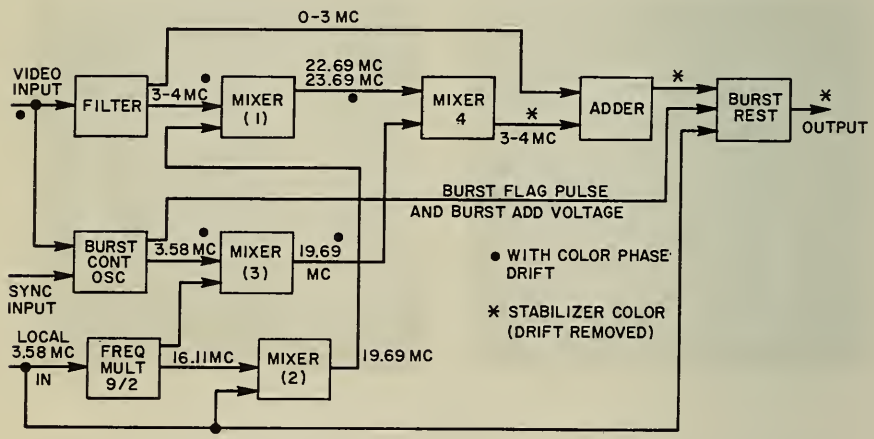


Fig. 9-2. RCA color-correction system.

contains all the color information. The lower frequency band is sent to an adder where it eventually recombines with the higher frequency band. The 3- to 4-mc band obtained from the filter is delivered to a mixer (1) where it is added to another signal, derived from the local 3.58-mc oscillator.

Local 3.58-mc signals are fed into a frequency multiplier unit that provides two outputs, both at 16.11 mc. One of these feeds a mixer (2) where it is combined with the local 3.58 mc from the station equipment, to provide a

19.69 signal which is then delivered back to mixer 1, and heterodyned with the 3-4-mc band derived from the video signal, producing an output frequency equal to the sum of the two input frequencies. Actually, this sum is a band of frequencies extending from 22.69 mc, to 23.69 mc. Further, since the 3-4-mc band includes phase errors produced by incorrect head-wheel speeds, the mixer output contains these same phase errors.

In the burst-controlled oscillator, video information, sync, and blanking, are stripped out of the incoming composite signal, leaving only the burst. This triggers an oscillator circuit that is allowed to operate for approximately 63 microseconds, the length of one horizontal line. The oscillator frequency is 3.58 mc, but its relative phase is controlled by the phase of the triggering burst. At the end of 63 microseconds, another burst enters the oscillator circuit and re-triggers it. Thus, line by line, the output phase of the burst-controlled oscillator is an exact replica of the phase of the color subcarrier as it comes off the tape.

Output from the oscillator is fed to still another mixer (3) where it combines with the second 16.11-mc signal from the subcarrier converter. Again the output frequency of the mixer is the sum of the two input frequencies, or 19.69 mc. Also, this output contains the same phase errors as the original video input, since it was derived from the burst. The 19.69-mc output from mixer 3 now goes to a fourth mixer (4) where it is combined with the 22.69-23.69-mc band from mixer 1. In this circuit the output is the *difference* in frequency between the two inputs, or a band of frequencies from 3 to 4 mc. What is more, since the two inputs to this fourth mixer contain identical phase errors, subtracting one from the other cancels the error, thereby providing a phase-corrected signal of from 3 to 4 mc. It is this signal that is fed to the adder, where it is recombined with the 0-3-mc signal from the filter to produce a composite color video signal.

There remains yet another correction, for the burst itself must be replaced. A pulse called the *burst flag* is generated in the burst-controlled oscillator, and sent to the burst restorer. Local 3.58-mc signals from the station oscillator are fed into the restorer, as is the corrected video signal from the adder. A d-c control voltage (burst add), and sync pulses from either the station sync generator, or the sync-restorer circuits, are also sent in to the burst restorer. The sync pulse is delayed slightly and widened, then used to clamp out the old, deformed, burst. The burst-flag pulse, operating in conjunction with the burst-add voltage and widened sync, activates a gating circuit that passes the local 3.58-mc signal for exactly the correct period, thereby generating a new, clean burst. This is added to the composite corrected signal to provide a complete color signal ready for transmission.

Let us now examine the circuits in somewhat more detail. The entire color system is contained in four assemblies, the *subcarrier converter, chroma processor, burst oscillator*, and *burst restorer*. Each will be discussed separately.

Burst Oscillator: A block diagram of this is shown in Fig. 9-3. Sync from the sync restorer is delivered to phase splitter V15. One output of the splitter is sent directly to V16, the other goes through a 3.75-microsecond delay line.

V16 sharpens the pulses and feeds them on to gate V13. The delayed output from V15 is also sent to gate V13, where it is used to permit the trigger pulses to pass only *after* horizontal sync has occurred. The output pulses of the gate then trigger multivibrator V12. The mark-space ratio of this circuit is controlled by the trigger pulses which, in turn, are fixed in time by the delayed input to the gate. The resulting multivibrator output (a pulse just slightly wider than the

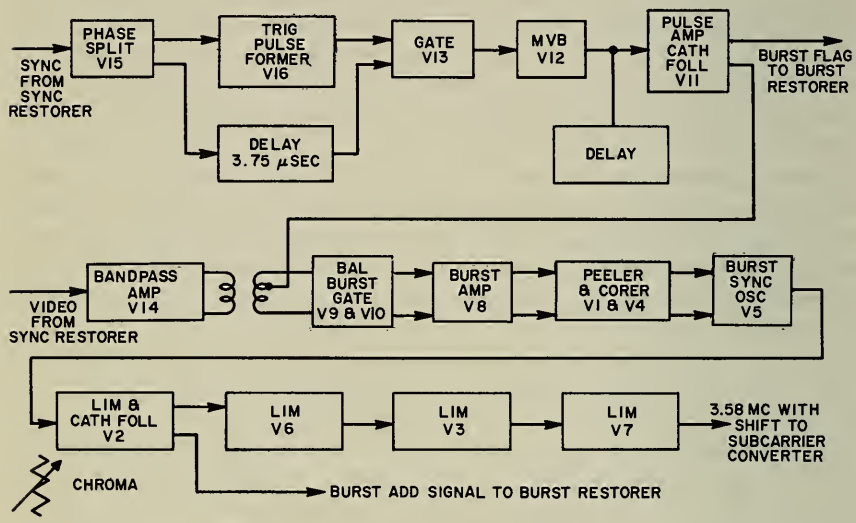


Fig. 9-3. RCA burst-controlled oscillator.

time required for 9 cycles of oscillation at 3.58 mc), is therefore timed to coincide with the start of the burst. After another delay (to allow the video signal passing through the other circuits to catch up with the pulse), the multivibrator output is amplified in one half of V11 and fed out to the burst restorer. This is the burst-flag pulse.

Video from the sync restorer is fed to bandpass amplifier V14, and transformer-coupled to balanced-burst gate V9 and V10. The gate is opened by a pulse from the cathode follower section of V11. Due to the gating action, only burst information is passed, all video and sync being removed. The burst is then sent into amplifier V8 and on to a "peeler-and-corer" (V1 and V4). This is the imaginative name given to a set of clippers which not only slice off the positive and negative peaks (peeling) of the burst, but also remove a piece through the center (coring). Any extraneous noises that might be riding in with the burst are therefore removed. Since the peeler-and-corer circuit is balanced, the outputs add when the remaining burst signal is transformer-coupled to the burst-synchronized oscillator, V5.

The oscillator itself is essentially conventional. When a burst is applied to the circuit, the first cycle of the burst triggers the tank circuit, causing it to start oscillating at 3.58 mc with a phase dependent upon the oscillator circuit itself. Succeeding cycles of the burst do not affect the frequency, but they do change the output phase so that, when the last cycle of the burst comes along, the oscillator phase is the same as that of the burst. Since no further information is delivered to the oscillator, it now continues to oscillate at this phase until the next burst arrives, at which time the circuit once again undergoes any phase changes necessary to bring it into step with the burst. The action continues, line by line, with the output phase at any time being determined by the preceding burst phase.

The output from V5 is fed into V2, V6, V3, and V7, a chain of limiters used to ensure that there is no amplitude variation in the signal. The final output is sent to the subcarrier converter, with a d-c component tapped off between V2 and V6 to act as the burst-add voltage in the burst restorer. If no burst is present, the oscillator, of course, does not operate, and the burst-add voltage disables the burst-restorer circuits so that no burst is placed in a monochrome signal.

Subcarrier Converter: The circuits of this assembly are illustrated in Fig. 9-4. Local 3.58-mc signals from the station sync generator are fed into V1, a

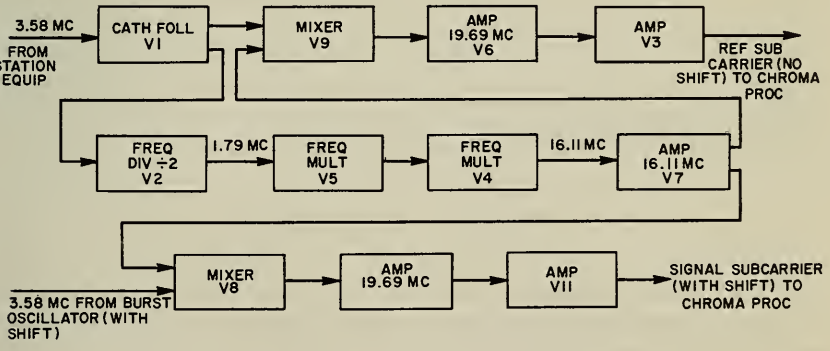


Fig. 9-4. RCA subcarrier converter.

cathode follower, which delivers its output to two stages, a divider and a mixer. Divider V2 cuts the frequency in half, producing a signal at 1.79 mc. This is then sent to an oscillator-type frequency multiplier, V5, where it is tripled to 5.37 mc. V4, another tripler, increases the frequency to 16.11 mc, and passes the result to amplifier V7. One of V7's two outputs goes to mixer V9 where it is heterodyned with the 3.58-mc signal from V1, producing an output of 19.69 mc. After amplification in V6, this signal is fed through cathode follower V3 to the chroma processor.

The other output from V7 is fed to mixer V8. This stage receives the 3.58-mc signal from the burst-controlled oscillator, and the two inputs are combined to produce 19.69 mc (containing hue phase shifts). V10 and V11 are identical to V6 and V3, and V11 delivers the signal through a cable to the chroma processor.

Chroma Processor: Figure 9-5 illustrates the operation of this unit. Video from the sync restorer is fed simultaneously into amplifiers V2 and V10, the

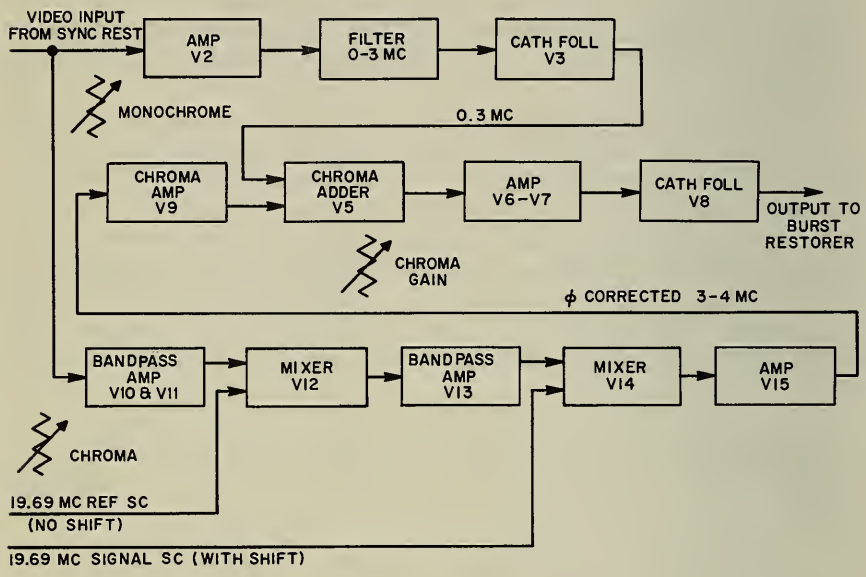


Fig. 9-5. RCA chroma processor.

former followed by a low-pass filter. The filter passes all frequencies below 3 mc, and has a sharp cutoff characteristic. After filtering, the remaining signal is sent through cathode follower V3 and on to chroma adder V5 for recombining with the 3-4-mc band removed by the filter. Amplifier V10, which also receives the incoming video signal, contains a bandpass circuit that passes only those signals lying between 3 and 4 mc. The resulting output from this stage is sent on to amplifier V11 and into mixer V12. The 19.69-mc signal derived from the local 3.58-mc equipment (and therefore free of phase shift), is injected into mixer V12, and the two signals heterodyned to produce a band of frequencies from 22.69 mc to 23.69 mc which now contains the hue phase shift from the video signal. This output is amplified in V13 and sent to mixer V14, where it is combined with the 19.69-mc signal derived from the burst-controlled oscillator, a signal that also contains the hue phase shift.

Here, as indicated previously, the output is the difference between the two

input frequencies, a band of from 3 to 4 mc, with the phase shift removed. V9 and V15 amplify this band of frequencies and pass it on to chroma adder V5. The two inputs to the adder (the 0-3-mc monochrome signal from the low-pass filters, and the 3-4-mc phase-corrected band), are combined into a single composite signal that is further amplified in V6, V7, and V8. Finally, the signal is fed out through a cable to the burst restorer.

Burst Restorer: This is the final link in the chain of RCA color circuitry, and is shown in Fig. 9-6. The phase-corrected color signal from the chroma processor is fed into the burst restorer at V1 and passes in succession through V2, V10, and V3. Clamping pulses are applied in the inputs of both V2 and V10 to remove the old burst. The new burst is added to the signal in V10, and V3 amplifies the resulting composite signal. The output of V3 is sent, via cable, to a color-distribution amplifier.

In order to remove only the burst, sync pulses from the sync restorer are used to key the clamping circuits. Incoming sync is first delayed 3 microseconds in a delay line, so that the start of the keyed clamp pulse will coincide with the start of the burst. The delayed sync is then amplified and differentiated in V4B, after which it is sent to multivibrator V5, a circuit that acts as a pulse former, manufacturing the clamping pulse. After clipping (to ensure flat tops), V6 amplifies the clamp pulse and splits it into two phases, which are then sent to V7 and V8, the clamp tubes.

Burst-flag pulses from the burst-controlled oscillator are delivered to V9, as is the burst-add voltage. The burst-add voltage opens the gate only if a burst originally triggered the burst-controlled oscillator. In the absence of an original burst, the gate is closed, and the burst-flag pulse does not pass through. The output of the gate, roughly corresponding to the burst timing, is then sent to burst keyer V11. Another pulse, from phase splitter V6, more accurately timed to the burst, also feeds into V11. The combination of pulses actuates the burst keyer at the exact instant required for the burst.

Signals from the local 3.58-mc station equipment are fed through a phase-shifting and delaying network so that the appropriate timing will be obtained for either record or playback operation. (In record, remember, the video signal is fed from the modulator to the demodulator directly, for monitoring puposes.) The output fom the phase-shifting network is also applied to the burst keyer, which now acts as a gate, permitting the 3.58-mc signals to pass only when the keying pulses are present. The output of this stage, then, is a brand new burst, and it is delivered to V10, the burst adder, for inclusion in the video signal.

Ampex Color Conversion

Color conversion in the Ampex machine follows a somewhat different approach than in the RCA machine, but the end result is the same. The phase-shifted chroma signals are restored to their correct relationship, and a new burst is added to the signal. The diagram in Fig. 9-7 shows the major components of

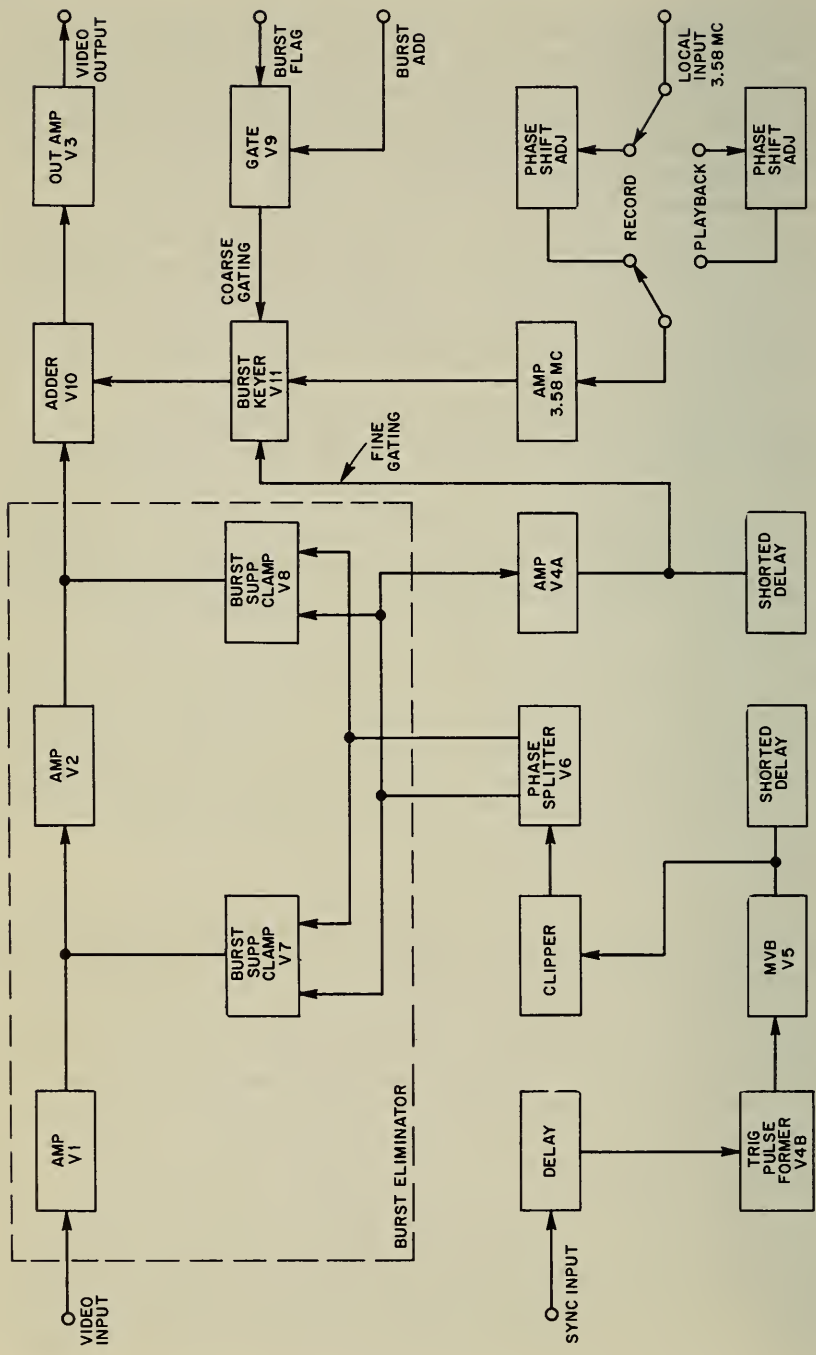


Fig. 9-6. RCA burst restorer.

the system. Video from the demodulator is fed into two units, a *color lock*, and a *decoder*. The color lock contains the necessary circuits to provide a color-killer signal, delayed sync, and 3.58-mc oscillations at the same phase as the uncorrected subcarrier from the tape. The outputs are fed to the decoder along with the composite video signal. In the decoder, the video signal is split into its *I*, *Q*, and *Y* components, with the subcarrier removed. These three outputs from the decoder are then sent to the *encoder*, where the *I* and *Q* signals modulate a new subcarrier from a local 3.58-mc generator. The resulting chroma signal is added back to the *Y* signal to provide a phase-corrected composite-color signal that is

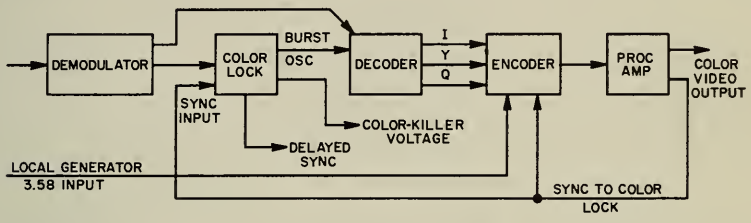


Fig. 9-7. Ampex color-correction system.

sent on to a new processing amplifier (replacing the unit used for monochrome) where sync and burst are both restored to normal.

In addition to the new components, the Ampex color conversion includes a redesigned modulator, demodulator and switcher. These are necessary because of the extreme linearity required by color signals. Essentially, the color modulator and demodulator are the same as those used in the RCA recorder (Chapter 8). The switcher incorporates more linear video circuits and provides for different timing.

Color Lock: Negative-going sync pulses from the processing amplifier enter amplifier 010A, as shown in Fig. 9-8, a block diagram of the color-lock unit. They are both amplified and differentiated in this stage, and then used to trigger multivibrator 011 at 15,750 cps. The positive-going portion of the multivibrator output coincides with the start of the sync pulses, and the mark-space ratio is adjustable. The output of 011 is used to trigger 012, another 15,750-cps multivibrator. Output pulses from this circuit have a trailing edge occurring roughly one horizontal line later than the original sync-pulse input. The exact position of the trailing edge may be adjusted to occur anywhere from several microseconds before, to several microseconds after, the horizontal blanking interval. The trailing edge is used to trigger a third multivibrator, 013, which has a mark-space ratio set to provide a 4- to 5-microsecond pulse at a rate of 15,750 pulses per second. These are sent through clipper-amplifier 014, and on to the color switcher, where they cause head switching to occur during horizontal sync rather than on the back porch.

Another output from clipper-amplifier 014 is sent to a gating circuit in the color lock. The pulse is first delivered to 001, a conventional amplifier. Amplified pulses from this stage are differentiated and fed to a ringing circuit to provide a delay, and then through amplifier-clipper 002B. From 002B they are delivered to both 003A and 003B simultaneously. Tube 003A is a conventional

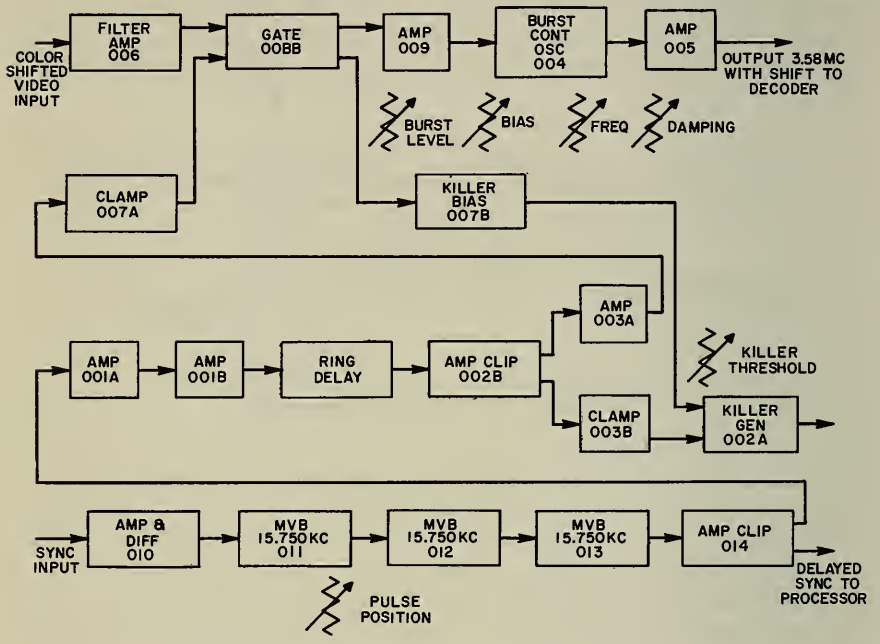


Fig. 9-8. Ampex color lock.

amplifier used to feed the delayed pulses to clamper 007A, and on to gate 008B. The other half of 003 is a clamped amplifier whose output is sent on to 002A, the killer generator. As this last circuit requires two inputs, we must first go back and develop the second signal before discussing its operation.

Composite video signals from the demodulator are brought into the unit and amplified in 006, a dual-triode amplifier. The first half of the tube incorporates a high-pass filter that eliminates low-frequency components in the signal. The second half of the stage contains a circuit tuned to 3.58-mc, and the output from this circuit is sent to gate 008B, the stage that received the clamped gating pulse (above). This circuit (008B) passes the 3.58-mc signal only when the gating pulse is present, thereby isolating the burst from the balance of the video signal.

When the gate is opened, and a burst appears in the output of 008B, diode 007B generates an adjustable negative voltage that is sent on to killer generator

002A, biasing it beyond cutoff. If a burst is not present, the bias is not applied, and the pulses fed into 002A from 003B are passed into a long time-constant R-C network that produces −40 volts. This is the color-killer voltage, and it is fed out to other components of the color-conversion equipment to disable them when only monochrome is being played back.

A second gated burst signal is taken from 008B and passed on to amplifier 009. The amplified burst is used to trigger burst-controlled oscillator 004, which operates in a manner similar to that of the RCA oscillator. The resulting 3.58-mc oscillation, varying in phase from line to line, is amplified in 005 and fed out to the color decoder.

Color Decoder: Figure 9-9 illustrates the Ampex decoder. The 3.58-mc signal from the burst-controlled oscillator in the color-lock unit enters the decoder, and is applied to amplifier 014. Some limiting is done in this stage, and the signal is passed to amplifier 009, also a limiter. The output of 009 feeds driver 013 which provides two outputs, one directly, the other through a 90° phase-shifting network. Each output is next routed to an additional phasing network to split the signals into 0° and 180° components. Thus, there are now four 3.58-mc signals, all with uncorrected phase, appearing at 0°, 90°, 180° and 270° with respect to the original burst phase. These are applied to 012, 018, 016 and 021 respectively. Each of these stages is a synchronous detector, or gated demodulator, that requires both a modulated color signal and an unmodulated local signal to produce a video output.

Video signals from the demodulator are fed through a level control into 003, an amplifier with two outputs, one for the *Y* signal, the other for the chroma signal. Actually, in this stage both signals are identical, as they have not yet been filtered to provide separation. The chroma output is fed to 005, an amplifier, and through a low impedance, high-pass filter that permits chroma information to pass, but rejects any luminance signals. The filter output is applied to 007, a cathode-anode follower circuit used to provide a low-output impedance for the chroma signal, which is now fed simultaneously to the grids of all four synchronous detectors. Stages 016 and 012 demodulate the chroma signal along the *I* axis, while 018 and 021 perform the same task for the *Q* component. A bias adjustment is available to compensate for slight differences in tube characteristics. The output of 016 is a positive *I* signal, that of 012 negative. Both are passed through a pair of sharp rejection filters that eliminate any 3.58-mc component remaining in the signal. The signals are then sent on to 015 and 011, a pair of amplifiers with their outputs in parallel. Here, the $+I$ and $-I$ components are added together to form a complete *I* signal that is fed through cathode-anode follower 010 to a delay line that eventually delivers the signal to the encoder. The *Q* circuit is identical except that no delay line is used, so cathode-anode follower 019 feeds a low-impedance transmission line. A low-pass filter is included in the output circuits of both 010 and 019 to remove any spurious components.

The video signal from 003 passes through a *Y* level control to phase splitter

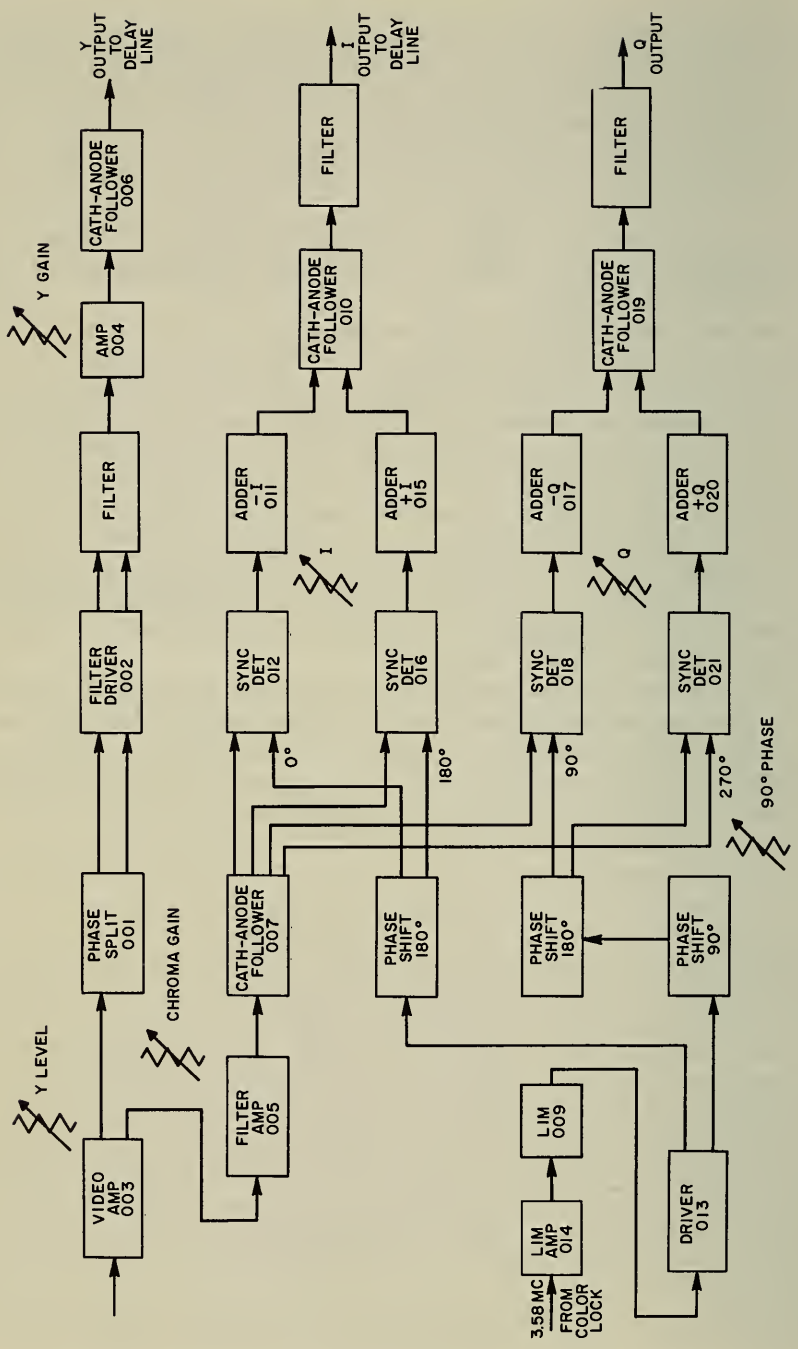


Fig. 9-9. Ampex color decoder.

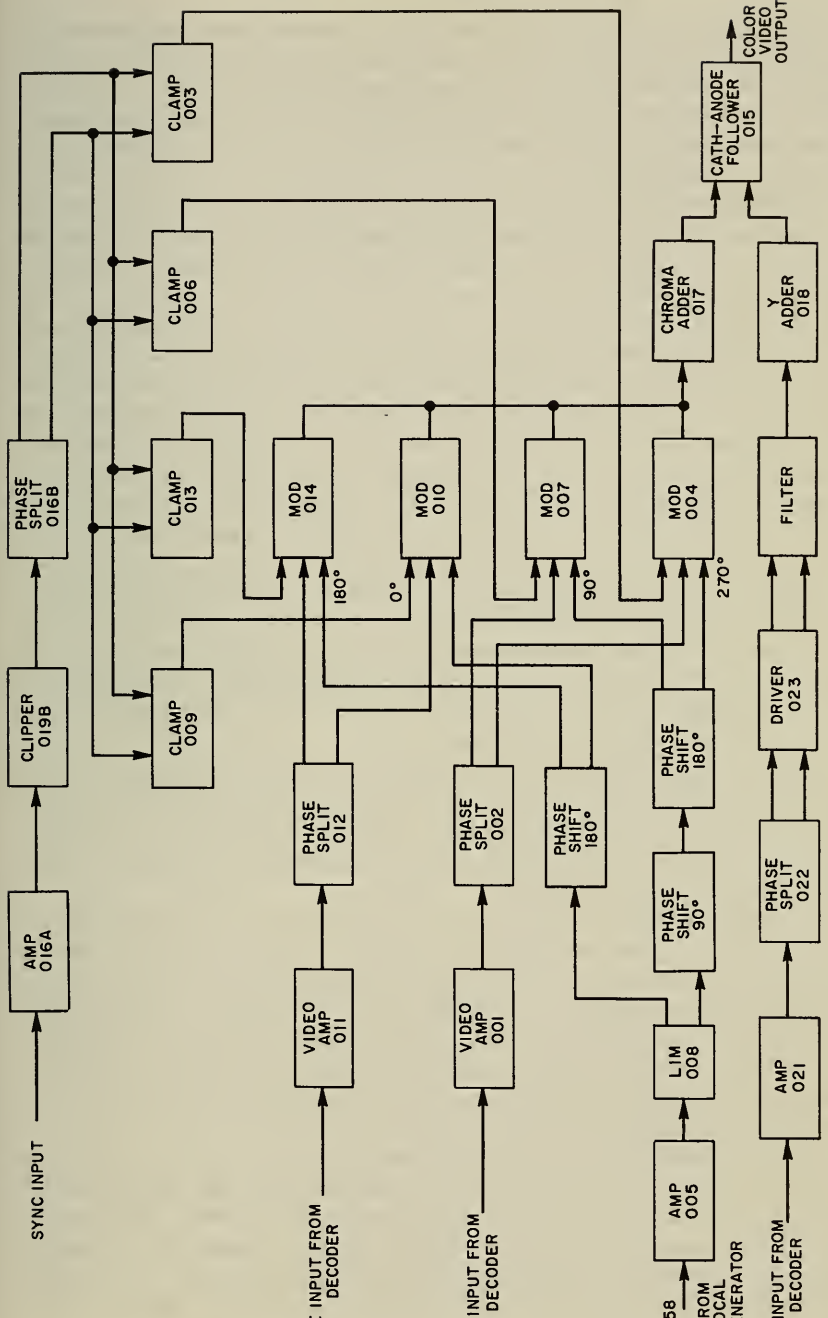


Fig. 9-10. Ampex color encoder.

001, which in turn, drives both halves of 002, a double triode. Both outputs of 002 then feed a special filter that reduces the amplitude at 3.58 mc quite sharply. The filter output is sent through amplifier 004 and on to cathode-anode follower 006, where another delay line delivers the *Y* signal to the encoder. The delay lines used with the *Y* and *I* signals permit them to be properly timed with respect to the *Q* signal.

Color Encoder: This circuit is the opposite of the decoder. It takes the decoder outputs, *I*, *Q* and *Y*, and recombines them into a composite video signal centered on a new subcarrier from the station's 3.58-mc oscillator. The block diagram is shown in Fig. 9-10.

Signals from the station subcarrier oscillator are fed into amplifier 005, and then on to amplifier 008, which acts to limit the signals and remove any amplitude variations. The output of 008 is fed through phase-shifting networks to modulators 010, 014, 007 and 004. There is no shift in modulator 010, but the others are shifted by 90°, 180° and 270°, as shown in the diagram. At the same time, the *I* signal is fed into 011, a conventional video amplifier incorporating a gain control. Output from 011 is sent to 012, a phase splitter, to provide two signals of opposite polarity ($+I$ and $-I$). The positive *I* signal is fed into 010, the negative *I* signal to 014. The plates of these two tubes are tied together. The subcarrier components appear in the output as two identical signals 180° out of phase, and they therefore cancel each other. The modulation products, however, remain, and are added to each other to produce a part of the standard chroma signal. The *Q* channel operation is identical, and the two outputs, one from the *I* channel, the other from the *Q* channel, are also added, producing a chroma signal with corrected phase shift.

To ensure proper operation of the modulators, negative sync pulses are sent into 016A, amplified, differentiated, and fed into 019B to be clipped. Positive pulses are derived from the clipper, fed to phase splitter 016B, and from this stage to four clampers, 009, 013, 006 and 003, that provide clamping action for the video signals in the modulators.

The *Y* signal from the decoder is sent to the encoder and fed into 021, a standard video amplifier associated with a level control. From 021, the *Y* signal is fed to phase splitter 022 and into a low-pass filter to remove any remaining components at 3.58 mc. The filter output is then sent to 018, an amplifier whose output is connected directly to the chroma output from the *I* and *Q* channels. The combined signals, a composite video signal complete with corrected subcarrier phase, is then routed to cathode-anode follower 015, and fed out to the processing amplifier through a cable.

Processing Amplifier: The processing amplifier used for color is essentially the same as that for monochrome, but several changes made provide better operation. Video amplifiers throughout the processor, are flatter, and provide improved linearity. Remote-gain control 009 (in the monochrome processor) is eliminated in the color circuitry, as is the white-stretch control. A new burst is added in at 003, together with the reformed sync pulse. In addition, blue

and cyan signals extend above the blanking level in a color signal, and for this reason, the black clipping level has been changed so that this hue information is not lost. Also, since switching now occurs in the sync interval rather than on the back porch, a phantastron circuit is incorporated, having a pulse width equal to the sync pulse. The phantastron is triggered by the processed sync, and the output fed into a gating circuit that adds the pulse to horizontal sync except during the vertical-blanking period. A pulse derived from the old blanking generator is used for the burst-flag system (not shown in the diagrams).

Color Switcher: In this unit, the r-f stages are altered to provide more linear characteristics. Further, the blanking switcher is incorporated into the overall assembly, while the sync pulses used to time the switching action are derived from the color lock instead of the processor. A delay is provided by a pair of multivibrators so that the switching action occurs at the sync tips instead of at the back porch.

Chapter 10

SERVO CIRCUITS

A number of circuits used in both the Ampex and RCA recorders, although known in the engineering field, are not often discussed in television texts, and may be unfamiliar to a great many people. Some of these circuits represent new applications of previously designed systems, while others are new both in application and design. To provide further understanding of the video recorders, these are discussed in detail here. It is, of course, impossible to include every circuit, so a representative number have been chosen. The circuits used in the servo systems of both machines are included in this Chapter. Chapter 11 discusses in detail some of the video circuits. Cathode followers also, although used in the servo systems, are discussed in Chapter 11. In the descriptions below, some components have been omitted for purposes of simplification.

Ampex 60-CPS Pulse Generator

In the Ampex drum-servo unit, a 60-cps pulse generator is used to permit synchronizing the machine to the incoming power-line frequency. The circuit of the pulse former is shown in Fig. 10-1. Essentially, this is a neon-bulb sawtooth generator with certain modifications that provide a pulse output. First, instead of dc being applied to the neon bulb (V1), ac is used. In order to provide sufficient voltage for triggering the bulb, the circuit is fed from the 6.3-volt tube heater supply. The transformer steps this up to 117 volts, a value impressed across both R1 and the neon bulb. If the neon bulb were removed, and R1 connected to ground, the voltage e would be impressed across the resistor. Since it is ac, it would vary from zero up to approximately 170 volts, the peak value of a 117-volt rms sine wave. However, V1 is effectively in series with R1, and so this voltage is applied across the series combination. Now, a neon bulb

will not pass current until the voltage across its terminals exceeds a certain minimum amount, called the *firing point* of the bulb. When this voltage is reached, the gas in the tube ionizes, and the tube conducts. Furthermore, it appears as a very low resistance in the circuit. Once the bulb has ionized, it requires somewhat less voltage to maintain the current through the tube, but if the voltage is decreased sufficiently, another point is reached at which the voltage just cannot maintain the ionization any longer. The ionization ceases, the tube loses its glow, current through it stops, and does not start again until the firing

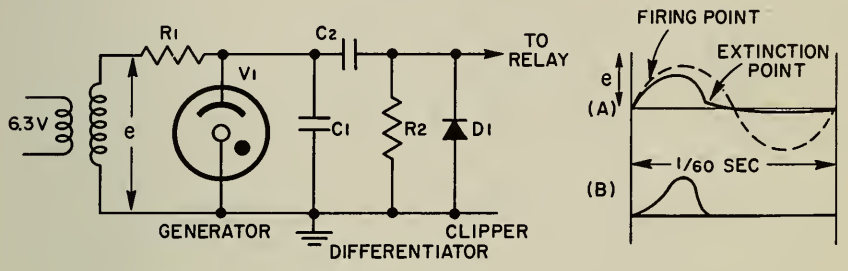


Fig. 10-1. Ampex 60-cps pulse former with waveforms.

point is again reached. With these thoughts in mind, we may now examine waveform *A*.

Let us assume that the input sine wave starts at zero volts (if it doesn't, we will merely be examining the conditions during the second cycle of the input). The dotted line indicates the input voltage from the transformer secondary. As this voltage increases, eventually the firing point is reached. At this time the bulb conducts, and R1 and V1 become effectively a voltage divider across the transformer secondary. Since the resistance of the bulb is now quite low, the voltage appearing across it will be lower than the applied voltage, as the solid line indicates. As the input voltage starts to decrease, the extinction point is reached, and the bulb stops passing current, causing the voltage across the tube to decrease more slowly due to capacitor C1. Actually, then, the neon bulb has produced a pulse, shown by the solid line. During the negative half cycle, the neon bulb cannot fire, so the only output from the circuit is due to a slight charging on C1. The output pulse from the bulb circuit is applied to a differentiating network composed of C2 and R2, which sharpen the pulse. Differentiators, however, produce both positive and negative components from an input pulse, so a clipper is added to remove the negative section. At any time when the voltage from the differentiator is less than zero, the cathode of diode D1 is negative with respect to its grounded anode. The diode therefore acts as a short-circuit and eliminates the negative component. The final output pulse is shown at waveform *B*.

Ampex Phase Comparator

Figure 10-2 illustrates the circuit of the phase comparator used in both the positional and velocity-error detectors of the Ampex drum-servo unit. The two triodes shown are the phase splitters that provide equal but opposite pulses to

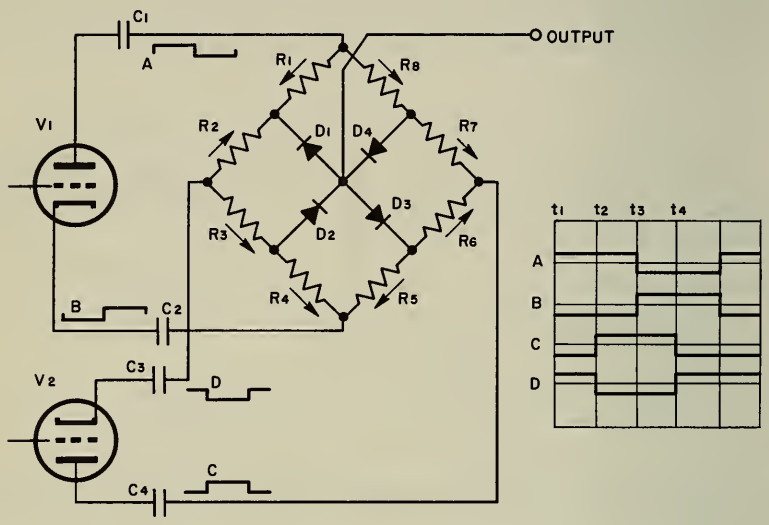


Fig. 10-2. Ampex phase comparator.

the bridge circuit. Pulses from the ringing oscillators in the servo unit are fed into V1. The outputs from this tube are waveforms *a* and *b*. Their instantaneous polarity is indicated in the diagram. Similarly, pulses from the head-wheel circuit feed into V2, producing waveforms *c* and *d*. Capacitors C1 through C4 act as coupling-capacitors and prevent the d-c operating voltages from affecting the bridge.

The action of the circuit starts at time t_1 in the waveform diagram. At this instant, waveform *a* is positive, and so current appears in both R1 and R8 in the direction indicated by the arrows. At the same time, waveform *b* is negative, causing currents in both R4 and R5, again in the direction shown by the arrows. At t_1, too, waveform *c* is negative, and is applied to the junction of R6 and R7. Currents in these two resistors are as indicated by the arrows. Finally, waveform *d*, positive at time t_1, is applied to the junction of R2 and R3, causing currents in these resistors also, again as indicated by the arrows.

Now, if the tubes are substantially similar, the currents created in all eight resistors will be equal. However, the current through R1 is traveling in a direction opposite to that in R2. Since the currents are equal and opposite, they can-

cel, and the net voltage at the junction of R1 and R2 is zero. Thus, diode D1 has zero volts applied to it, and nothing happens. An identical situation exists at the junction of R5 and R6, where the two currents are also traveling in opposite directions. Diode D3 is therefore nonconducting. The currents in R7 and R8, on the other hand, are both moving in the same direction. This being so, R7 and R8 act as a voltage divider, the applied voltage being the difference in amplitude between waveform *a* and waveform *c*. A voltage then appears across diode D4 and it conducts. Simultaneously, the currents in R3 and R4 are in the same direction, producing a voltage at their junction, which in turn, permits diode D2 to conduct. Inasmuch as the diodes are joined together in a common connection, the outputs from D2 and D4 are added together to provide a single output that is positive, due to the diode and applied voltage polarities.

The output remains constant at some positive value until time t_2. At this instant, waveforms *c* and *d* are reversed, but waveforms *a* and *b* remain the same. Thus, the currents through R1, R4, R5 and R8 are unchanged, but those through R2, R3, R6, and R7 are reversed. Diodes D2 and D4 now see 0 volts applied to them, and they stop conducting. Due to the reversal, however, diodes D1 and D3 have a voltage applied to them, and they both conduct, producing a negative-going output that continues to remain negative until t_3, at which time waveforms *a* and *b* are reversed, while *c* and *d* remain the same as they were. Again diodes D2 and D4 conduct, while D1 and D3 are open-circuited. The output pulse therefore becomes positive once more, and remains so until time t_4 when waveforms *c* and *d* again reverse themselves, causing D1 and D3 to conduct and produce a negative output pulse.

From t_1 to t_2, then, the output pulse is positive. From t_2 to t_3 it is negative. Thus, one complete cycle of output appears in this period, but this is the same period taken up by only a half cycle of the input 240-cps signals. The output is therefore a 480-cps wave, but the frequency is unimportant, for it is the d-c component of the output that becomes the error signal. In the event the time between t_1 and t_2 is exactly the same as the time from t_2 to t_3, and from t_3 to t_4, the resulting 480-cps wave will be perfectly square. Its d-c component is therefore zero, indicating there is no error in the head wheel. Should the head-wheel speed or position change, however, these time intervals will no longer be equal, as they depend upon the relationship between the two input waves. When this occurs, the output is no longer a square wave, but rather a rectangular wave. Such a wave has a d-c component, and its polarity depends only upon which period of the output is longer. Should the positive-going portion exist for a longer time than the negative-going segment, the d-c component will be positive. If the conditions reverse, the d-c component becomes negative.

Ampex Colpitts Oscillator and Control

Positional errors in the Ampex head drum are corrected by changing the frequency of a Colpitts oscillator in the drum-servo unit. The circuit of this oscil-

lator is indicated in Fig. 10-3. Capacitors C3 and C4 are coupling-capacitors, and need not be considered further.

Normally, the oscillator (V2) is tuned to 240-cps by the tank circuit of L, C1 and C2. If at any time diodes D1 and D2 are conducting, they are short-circuits, and capacitor C5, 0.0051 μf, is connected across the tank. However, the anode of D2 is connected directly to a source of +150 volts (the VR-150 regulator). Also, the instantaneous plate voltage of tube V1 is, for all practical

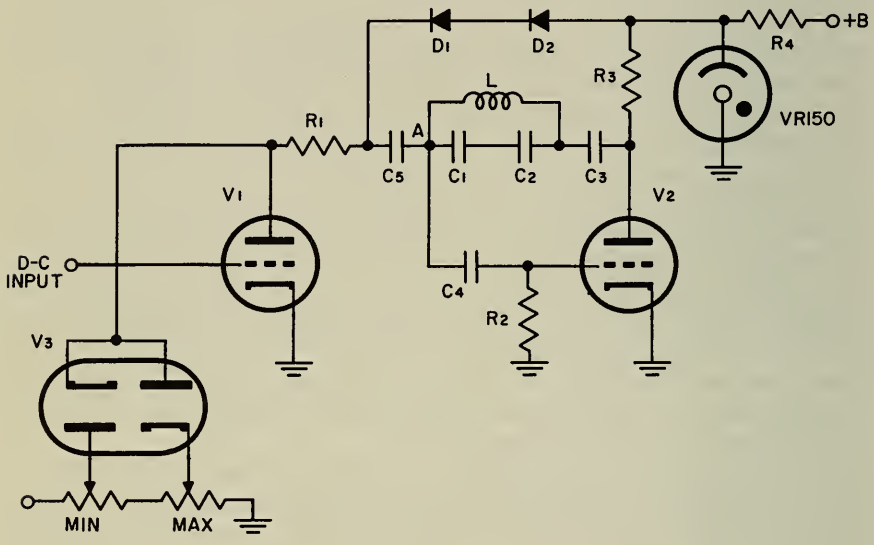


Fig. 10-3. Ampex Colpitts oscillator and control tube.

purposes, the voltage at point *A* (the junction of L and C5). If at any time this voltage drops below 150 volts, diodes D1 and D2 will start to conduct, inserting C5 across the tank. The amount of time that this capacitor remains in the tank circuit depends only upon the charge it has acquired prior to the diode conduction. In turn, the charge on C5, built up during the nonconducting period of diodes D1 and D2, is strictly dependent upon the grid signal in tube V1. But the d-c error signal from the phase comparator is the grid voltage for V1. Thus the error signal determines how long C5 remains in the tank circuit. Now, the frequency of oscillation is determined by the tank circuit. However, inserting the extra capacitor alters this somewhat, the exact amount of change being determined by the time the capacitor is in the circuit. If the error signal is zero, the capacitor is inserted for a brief period, just long enough to cause the oscillator to operate at 240 cps. Should the error signal be either positive or negative, the time of insertion is changed, and the frequency is accordingly altered. Posi-

tive-going error signals cause the output frequency to increase, while negative signals produce a decrease. Tube V3, a double diode, is used as a clamper to set the minimum and maximum values of plate voltage for tube V1. In this manner, the clamper also sets the minimum and maximum frequency excur-

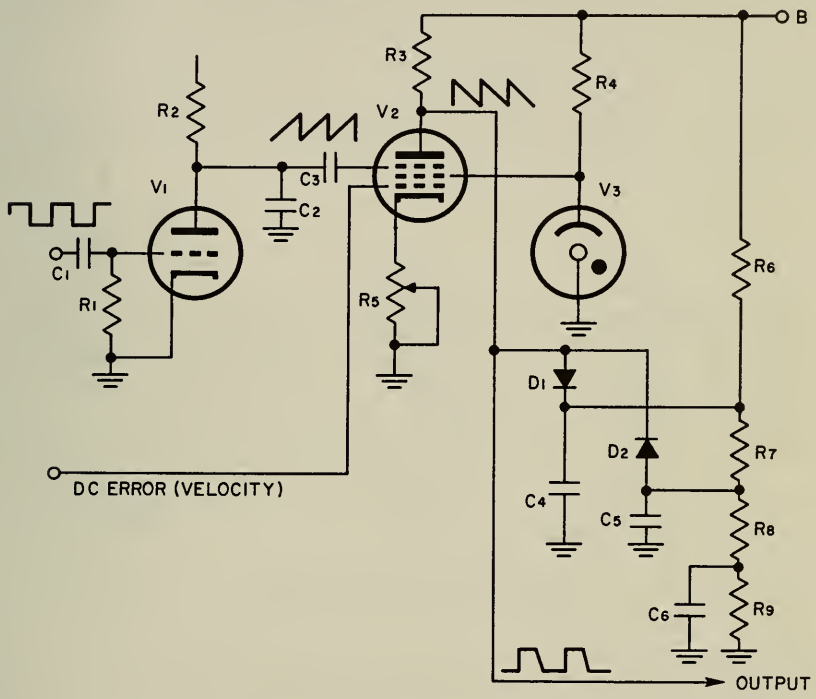


Fig. 10-4. Ampex sawtooth generator and clipper.

sions of the oscillator. C4 and R2 provide bias for the oscillator, while R3 acts as a dropping resistor. R1 sets the charging rate for C5.

Ampex Sawtooth Generator and Clipper

This circuit adds the positional and velocity errors in the Ampex drum-servo unit, feeding them out to the final oscillator that drives the head-wheel motor. The circuit is shown in Fig. 10-4. The input to V1 is a square wave, obtained from a multivibrator triggered by the Colpitts oscillator. V1 is a thyratron sawtooth generator. The square wave causes current to pass through the tube when the input is positive, and stops the current when the input is negative.

When the current is stopped, the d-c plate potential on V1 is equal to the applied operating potential, and capacitor C2 charges towards this value, through R2. When the tube conducts, the plate voltage is substantially reduced, and C2 discharges through the tube. The discharge is much more rapid than the charge, since the internal plate resistance of the tube is substantially lower than R2. The time constant of R2 and C2 is quite long, so during the charging period the capacitor voltage increases slowly, and linearly. The result is the sawtooth

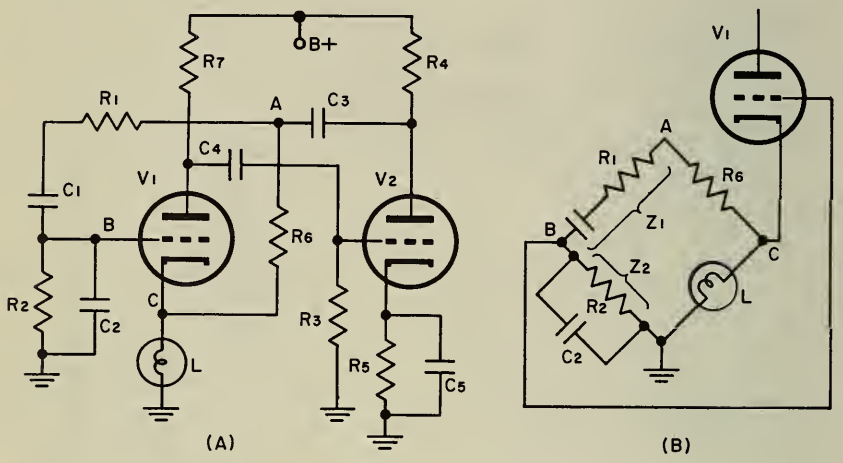


Fig. 10-5. Wien-bridge oscillator.

indicated on the diagram. Capacitor C3 couples the sawtooth to grid 3 of V2. C1 and R1 form a coupling network between the multivibrator and V1.

The sawtooth applied to V2 is amplified and inverted by the tube, which acts as an amplifier. However, the d-c plate voltage of the tube depends upon the instantaneous voltage on grid 1. This is the d-c error signal from the velocity-detector system. If it is zero, the d-c plate voltage is approximately 130 volts. The output sawtooth (75 volts p-p) centers itself on this value. If the d-c error signal applied to grid 1 becomes positive, the d-c plate voltage of V2 is reduced, and the output sawtooth, still 75-volts p-p, rides on this newer value. Should the input d-c error signal go negative, the plate potential increases, and the center axis of the sawtooth is moved to a higher value than 130 volts. Thus, although the sawtooth amplitude remains constant, its zero axis is shifted in accordance with the velocity-error signal. Resistor R5, a symmetry control, permits setting the desired zero axis when the error signal is zero. R3 acts as plate load for the tube, and R4 and V3 provide screen voltage.

The sawtooth output from V2 is applied across a pair of diodes, D1 and D2. Resistor R6 drops the supply voltage to 130 volts. Any output from V2 which

is more positive than this value causes D1 to conduct, at which time it acts as a short-circuit across the output. Thus, sawtooth voltage in excess of 130 volts is clipped off the output. Similarly, resistor R7 drops the supply voltage by one additional volt, providing a bias of 129 volts on diode D2. Due to the polarity of D2, any signals lower in amplitude than 129 volts cause this diode to conduct, and act as a short-circuit. R8 and R9 act as the remaining portion of the voltage divider that provides the necessary operating voltage for the diodes. C4, C5 and C6 are bypass capacitors. Due to the action of the diodes, only that portion of the sawtooth between 129 and 130 volts appears in the output. Since the sawtooth is moved up and down by the d-c error signal, the resulting output is a trapezoid, as shown, whose trailing edge will be shifted along the time axis by an amount determined by the zero axis of the sawtooth from V2.

Wein-Bridge Oscillator

The Wein-bridge circuit, used in the Ampex capstan-servo, is one of a family of oscillators that depends upon resistance and capacitance for tuning, rather than inductance and capacitance. It is easier to tune, and tends to remain much more stable than more conventional oscillators. The circuit from point *A* to ground in the actual oscillator may be redrawn as in Fig. 10-5, part (B). The combination of resistance, capacitance and the lamp, L, provides a bridge circuit, from which the oscillator derives its name.

For a circuit to oscillate, it must, in general, be supplied with positive feedback. When the feedback occurs at a number of frequencies simultaneously, the resulting oscillation is far from sinusoidal. A typical example, of course, is the free-running multivibrator. To provide sine-wave outputs, most oscillators rely on the usual tuned circuit to limit the feedback to a single frequency. This is the frequency at which the circuit oscillates. In the Wien bridge, two feedback paths are provided, one producing negative feedback, the other positive feedback. At any frequency where the negative feedback exceeds the positive feedback, the circuit cannot oscillate. On the other hand, when the positive feedback is greater than the negative feedback, the system does oscillate. It is the function of the bridge to see that the positive feedback is the higher quantity only at the desired frequency.

Consider the bridge circuit of part (B) of the figure. Let us assume that a sine-wave signal is applied across the bridge between point *A* and ground. The path through R6 and L is a simple voltage divider, so the voltage at point *C* is less than the input at point *A*. The other path, through the R-C network, is not quite so simple. The voltage at point *B* depends upon the signal amplitude at point *A* as well as the voltage divider action of Z1 and Z2, the two arms of the bridge in this path. These impedances, however, are dependent upon the values of the capacitive reactances in the circuit, which in turn, are determined by the frequency of the signal applied across the bridge. Suppose that R1 and R2 are relatively high resistances. At high frequencies, the reactances of both capacitors

will be small. Thus, C2 effectively short-circuits R2, and the voltage at point *B* is also small. At low frequencies, the reactance of C1, in series with R1, causes a large drop to occur in Z1, again reducing the voltage at point *B*. At some middle frequency, then, it seems apparent that the voltage at *B* will be a maxi-

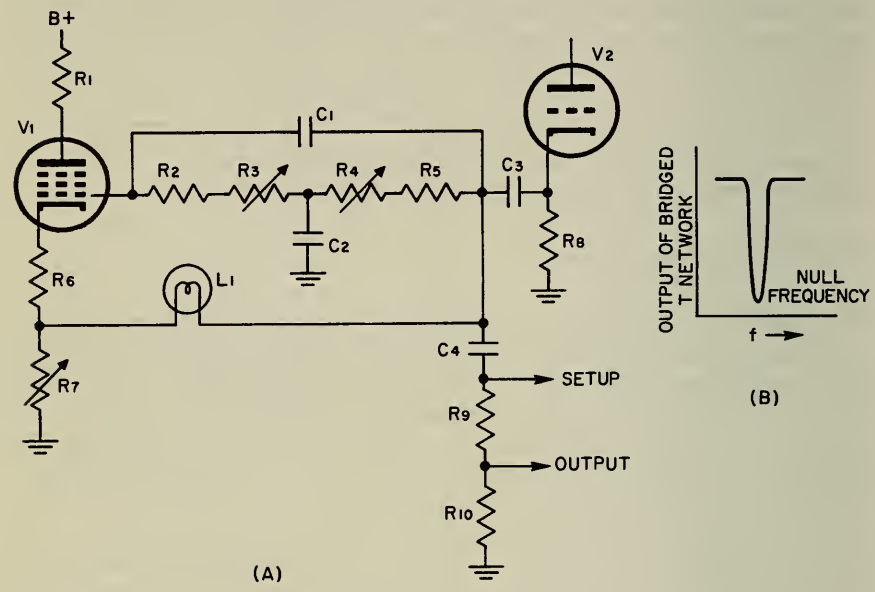


Fig. 10-6. RCA bridged-T oscillator.

mum. At any other frequency, the combined action of C1 and C2 will reduce the voltage.

Now, suppose that the values of all the bridge components are chosen so that the voltage at *B* is a maximum, and just barely exceeds that at *C* at some selected frequency. Frequencies either higher or lower than the desired frequency then produce lower voltages at *B*. But *B* is the positive feedback point, while *C* is the negative feedback point. By proper selection of the components, the positive feedback can be made to exceed the negative feedback, and the system then oscillates at the desired frequency. If the frequency is to be changed, it is only necessary to change one component in the R-C arms of the bridge. This changes the impedance of one of the arms, and causes the bridge to balance at a different frequency.

Theoretically the lamp, L, acts as a resistance in the circuit, and from the standpoint of feedback conditions, it could be replaced by a fixed resistor. In practice, however, the lamp serves a very useful function, for its resistance varies with the current through it. Thus, if the output of the oscillator tends to rise, more cur-

rent passes through the lamp, its resistance increases, and the negative feedback is increased. This tends to reduce the amplitude of the output. Conversely, if the output drops, the lamp resistance also drops, and the negative feedback is reduced, thereby increasing the output. The lamp is therefore a regulating device that maintains a constant amplitude output from the oscillator. The operation of the lamp does not affect the frequency, for if the signal amplitude changes, the feedback voltage at point *A* also changes, and the proportion of negative feedback to positive feedback is maintained.

Tube V2 in the circuit is an amplifier, and the output is usually taken from its plate circuit. In addition to amplifying, this tube also provides the additional inversion needed to obtain the in-phase feedback necessary for operation. R4 and R7 are plate-load resistors for the tubes, while C3 and C4 act as coupling-capacitors. Bias for the oscillator tube, V1, is furnished by the resistance of the lamp, while R5 and C5 furnish bias for V2.

Stabilized R-C Oscillator (RCA)

Figure 10-6 is a schematic diagram of the stabilized oscillator used in the TRT-1A recorder to drive the head wheel. Essentially, the circuit is a cathode-coupled form of the Wien-bridge oscillator, but it is more easily understood when drawn as shown in the diagram. In this configuration the frequency-determining components form a bridged-T null network between the two amplifier stages, and the circuit is therefore referred to as a *bridged-T oscillator.* Positive feedback is provided through the lamp (L1) from the cathode of V2 to the cathode of V1. Negative feedback from the cathode of V2 to the grid of V1 occurs through the network composed of C1, C2, R2, R3, R4, and R5.

Bridged-T networks, in general, provide a very sharp null, or rejection, at a single frequency, as indicated in part (B) of the figure. Thus, at the frequency to which the network is tuned the negative feedback in the circuit is decreased substantially, leaving only positive feedback, which produces oscillation. If the oscillator drifts off its assigned frequency, the null network, due to its sharp selectivity, applies negative feedback to V1, causing the oscillator to return to that frequency at which the positive feedback exceeds the negative feedback. The frequency of oscillation is set by adjusting the resistive arms of the bridge (R3 and R4). R2 and R5 are added so that the resistance will not drop to zero in the event the controls are inadvertently placed at the short-circuit end of their rotation. Both R3 and R4 are switched out and replaced by another pair of variable resistors for setup purposes. These latter are adjusted to provide a null at 240 cps rather than at 340 cps, the normal operating frequency of the oscillator.

As in the Wien bridge, the amplitude of oscillation is regulated by the lamp, which changes its resistance proportionally to the current flowing through it. In order to provide adequate stabilization in this manner, the oscillator must operate at a high level. For this reason a voltage divider (R9 and R10) is pro-

vided at the output to reduce the signal amplitude prior to applying it to the rest of the motor-drive circuits. The voltage divider is bypassed for setup operations, as shown. For the rest of the circuit, R7 adjusts the positive feedback, while R6 and R8 act as cathode-bias resistors. Capacitors C3 and C4 are coupling capacitors used to block any d-c component from the bridge network and the following stages.

Variable Phase Shifter

This circuit, used in the playback portion of the Ampex capstan-servo unit, permits shifting the relative phase of the output signal in order to adjust the position of the heads longitudinally along the tape during playback. In this manner, they may be made to pass directly over the center of the recorded tracks.

Both tubes in the circuit (Fig. 10-7) are conventional voltage amplifiers. V1 provides the variable phase shift, while V2 is used for isolation purposes. The

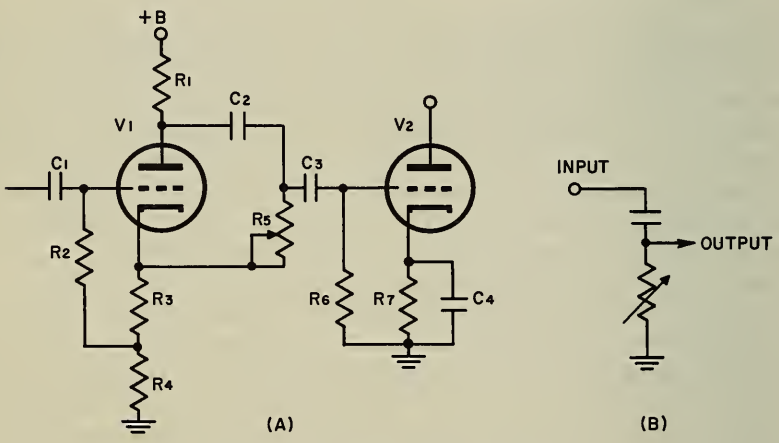


Fig. 10-7. Ampex variable phase shifter.

phase shifting is accomplished by varying R5. In conjunction with C2, this resistor forms a simple series network, as shown in part (B) of the figure. Suppose a sine wave is applied across C2 and R5. The output phase angle then depends upon the ratio of *reactance to resistance*, since the circuit is a simple R-C combination. If the resistance is changed, the relative output phase angle, with respect to the input, may be altered. Additionally, if R5 is changed the output amplitude of the circuit also changes, the new value depending upon the ratio of *resistance to the total circuit impedance.* In other words, the network is a variable voltage divider as well as a phase shifter. Changing R5 changes both the amplitude and the phase of the output.

Let us now return to the original circuit. Effectively, R5 is returned to ground through the cathode resistors, R3 and R4. C2 acts as a coupling-capacitor, but clearly, the effect of the series combination from the plate of V1 to ground (C2, R3, R4 and R5) is similar to that of the simplified circuit in part (B) of the

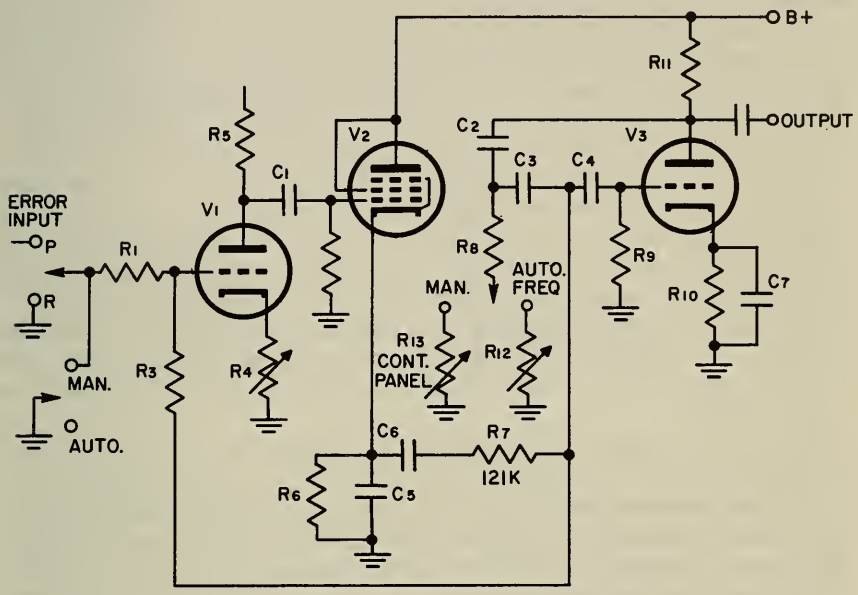


Fig. 10-8. RCA phase-shift oscillator and control.

figure. R5 therefore permits the output signal phase to be varied. R3 and R4 are essentially in series with R5, and prevent the total circuit resistance from ever reaching zero, which would short-circuit any output signal. At the same time, by connecting R5 to the cathode resistors, feedback is established in V1. This results in stabilization of the circuit, so that when R5 is varied, the output amplitude of the system at the junction of R5 and C2, remains practically constant. C3 prevents the d-c cathode potential of V1 from reaching the grid circuit of V2.

Phase-Shift Oscillator

The oscillator of the RCA capstan-servo system is illustrated in Fig. 10-8. This is another of the R-C tuned sine-wave oscillators. Basically, the circuit is composed of a tube and a feedback network. The oscillating tube is V3. From its plate, a feedback loop sends the signal back to the grid through three individual R-C phase-shifting networks. The output is taken from the plate of V3.

For the moment, disregard all the circuits of V1 and V2. Mentally place a resistor from the junction of C3 and C4 to ground. This is the basic configuration of the phase-shift oscillator. Each capacitor and resistor combination, C2 and R8, C3 and the imaginary resistor, C4 and R9, is a phase-shifting network capable of providing up to 90° of phase shift. Let us assume that all the capacitors in this arrangement are equal, as are the resistors. For oscillation to occur and be maintained, the feedback must be in phase, but there is only the one tube. It is therefore clear that if all three networks are the same, the system will oscillate only at that frequency which causes each network to produce a 60° shift. To illustrate, suppose the signal at the grid of V3 is the positive peak of a sine wave. At the plate, this would be inverted. We now need an additional 180° shift before the signal reaches the grid if oscillation is to be maintained. The value of the resistors and capacitors are so selected that each combination provides 60° of shift at the desired frequency. Thus, at the junction of C2 and R8, the total shift is 180° + 60°, or 240°. At the junction of C3 and the imaginary resistor, still another shift occurs, adding 60° to the total shift. Finally, at the junction of C4 and R9, there is yet another 60° shift. The total shift around the circuit is therefore 360°, providing in-phase feedback. In practice, each network need not be the same, as long as the total phase shift of all three networks is 180°.

The amount of phase shift produced by a simple R-C circuit depends upon the ratio of reactance to resistance, as we learned in the preceding section. If any of the components in the phasing networks are changed, the phase shift at the original frequency will also change, and the feedback will no longer be in phase at this frequency. The system therefore changes frequency, and oscillates at whatever frequency does provide the correct phase for the feedback signal.

In Fig. 10-8, the circuit of V2 acts as a variable resistor, controlled by the error signal. Essentially, V2 is a cathode follower, and its output impedance is the parallel combination of the cathode circuit impedance and the tube's plate resistance. This value, plus the 121-k resistor (R7) in series with the output of V2, is the resistive component of the 2nd phase-shift network. If it is varied, the oscillator frequency will also vary. Let us see how this change is accomplished.

A portion of the oscillator signal which appears at the junction of C3 and C4 is fed into amplifier V1 through a voltage divider consisting of R3 and R1. The signal is inverted in V1 and applied to the grid of cathode follower V2. The output is taken through C6, a blocking capacitor that prevents any dc from returning to the grid of V1. Since cathode-follower output voltages are in phase with their inputs, the voltage at the left side of R7 is out of phase with the voltage at the right side, which effectively causes the resistance seen by the phase-shift network to appear less than its actual value. The degree of reduction is controlled by the amount of amplification provided by V1 and V2. Now, the grid of V1 also receives an error signal developed from the control track and tone-wheel comparison network, and this voltage controls the amplification of

V1. When the error voltage rises, indicating reduced capstan speed, the amplification of V1 increases, causing the effective resistance to decrease, thereby changing the resistance-reactance ratio of the phase-shift network. In turn, this causes the oscillator frequency to increase. The capstan motor is of the synchronous type, so an increase in its drive frequency also increases its speed. In like manner, drops in the error voltage reduce the capstan speed. A control (R4) is provided to adjust the circuit initially for correct operation.

A relay-actuated switch is used in the 1st phase-shift section to provide automatic or manual operation and adjustment. In the manual position, R8 is con-

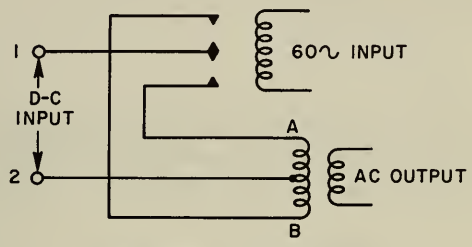


Fig. 10-9. Typical chopper.

nected to a variable resistor located in the control panel, while in automatic, it is tied in series with R12. The manual position permits altering the frequency (and therefore the capstan speed) directly from the control panel. Another set of contacts on the same relay (at lower left in the diagram) are used to short out the error signal for manual operation. Finally, a third switch disables the error-signal circuits in the record mode when the capstan is driven directly from the 60-cps lines.

Choppers

A chopper (Fig. 10-9) is essentially a driven vibrator. When 60-cycle power is applied to a coil, the coil alternately switches the center contact (the input connection) from one side to the other. In so doing, the chopper converts dc to ac. In the Ampex tape-guide amplifier, this resulting ac is used to control the vacuum shoe position.

Assume for the moment that the input at point *1* is dc, positive with respect to point *2*. When the armature of the chopper is in contact with the upper connector, point *B* on the transformer primary is positive with respect to the centertap. When the armature shifts and contacts the lower connector, point *A* on the transformer is made positive. Effectively then, the polarity of the signal across the transformer primary is alternated by the chopping action. The output is therefore a wave that is alternately positive and negative. The peak amplitude

of the wave is, of course, dependent upon the amplitude of the d-c input to the chopper.

If the input polarity should change, making point *1* negative with respect to point *2*, the polarities at *A* and *B* would be negative with respect to the center-tap. The resulting output from the secondary is then the same as before, but shifted in phase by 180° from that produced by the original positive input signal.

The frequency of the chopper output is fixed by the frequency that drives the armature, in this case 60 cps. One complete cycle of input causes the chopper armature to make contact with both connectors once. In turn, this provides one positive pulse and one negative pulse in the output. The waveform of the output from the transformer is, for all purposes, roughly square.

Phantastron

The phantastron circuit of Fig. 10-10, used in the Ampex automatic-compensation sensor, is really two tubes in one package. In the tube, the control grid determines the cathode current, which is made up of two components, plate

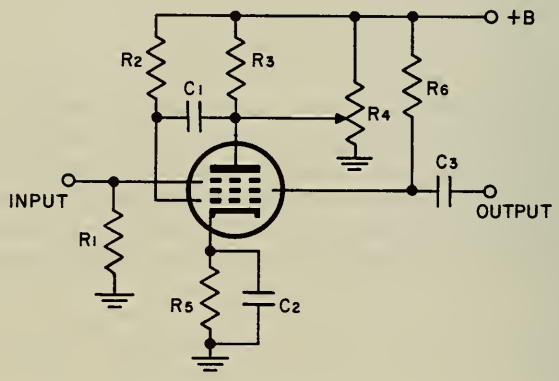


Fig. 10-10. Illustration of the phantastron.

current, and screen current. Grid 3, the suppressor, controls the division of the cathode current into its two parts.

For normal operation, the plate circuit is usually cut off, but the screen circuit is operating. The d-c voltage on grid 1 is obtained through a resistor from the B supply, making this grid slightly positive, with respect to the cathode. Thus, the cathode current is high, as is the cathode voltage. However, the input circuit, grid 3, is normally at ground potential, or negative with respect to the cathode. This stops the plate current. Under these conditions the cathode current is equal to the screen current. R4, the zero adjustment control, sets the plate voltage so that these conditions may be maintained.

Now, if a positive trigger pulse is applied to grid 3, plate current commences, and the plate voltage drops. The instantaneous change in plate voltage is coupled through C1 to grid 1 of the tube, causing both the cathode current and cathode voltage to become smaller. In turn, this makes the screen voltage rise suddenly, producing the leading edge of the output pulse. But if the cathode potential is lower than normal, the suppressor will appear to have gone positive with respect to its previous condition. The plate current therefore increases, and

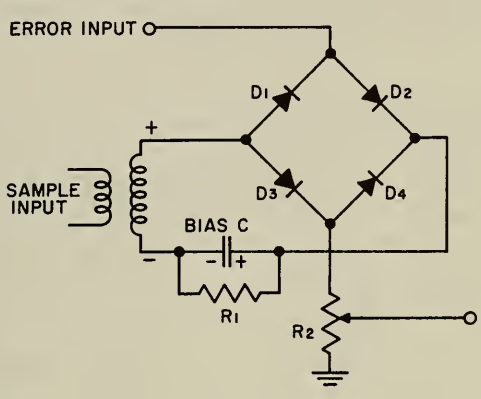


Fig. 10-11. Ampex sampler bridge.

the plate voltage drops even further, causing the chain of events started by the trigger pulse to continue until the plate voltage is so low that the system can no longer change. When this occurs, the plate side of capacitor C1 is at a fixed potential and the capacitor starts to discharge, causing grid 1 voltage to increase until the grid is restored to its normal positive value, at which time the cathode voltage again rises to normal, and the suppressor once more cuts off the plate current. The screen current then rises, causing the screen voltage to drop back to its normal value producing the trailing edge of the output pulse. After this, the system waits for another pulse to start the sequence over again.

It is of interest to note that in its early days, the operation of this circuit was considered to be *fantastic,* which is why engineers gave it the name it bears today.

Sampler Bridge

A diode bridge arrangement for sampling input signals is shown in Fig. 10-11. This is the circuit used in the Ampex automatic-compensation sensor. An error signal is fed in at the top of the bridge, and appears at the bridge output as dictated by the sampling pulse.

The sampling pulse input to the bridge is through the transformer. Negative

pulses will not get past D1 and D3, and are therefore of no consequence. However, if the sampling pulse is positive, the diodes conduct, and in so doing, charge capacitor C1 to the polarity shown. The combination of R1 and C1 is a long time-constant circuit, so C1 cannot discharge rapidly. After the pulse has performed its charging job, a positive voltage appears at the cathodes of D2 and D4, effectively blocking the path of the error signal through the bridge, as the

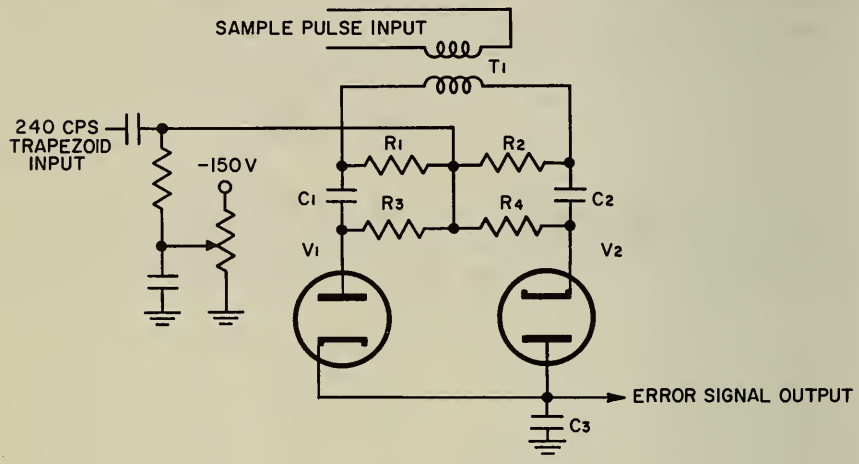


Fig. 10-12. RCA error detector.

diodes are cut off. Between sampling pulses, C1 discharges slightly, so when the next sampling pulse comes along, the diodes once more conduct, but only for the 2-microsecond period during which the sampler pulse is present. During this short interval the diodes appear as short-circuits and the error signal passes through the bridge, appearing as a voltage across R2. At the end of the sampling-pulse interval the bridge again blocks the error signal path until the next pulse comes along. Each sampling pulse, of course, also restores the small amount of charge that has leaked off the capacitor during the interval between pulses. In this manner, the error signal is blocked except for the short pulse interval. R2 acts as a sensitivity control and permits adjustment of the output amplitude.

RCA Error Detectors

The circuit of the error detector used in the RCA head-wheel servo is illustrated in Fig. 10-12. The circuits of the phase detector and velocity detector are identical except for the value of capacitor C3 and the sampling pulse. For phase correction, the pulses are 10 microseconds wide, and occur at a 60-cps rate, while the velocity detector utilizes 20-microsecond pulses at a repetition rate of

240 cps. Capacitor C3 is 1000 μμf in the phase error detector, and 4700 μμf in the velocity error detector.

In the detector circuit both diodes are normally off, that is, nonconducting. However, the polarity of the pulses delivered to the diodes by the transformer is such that the tubes conduct when the pulse is present. During the brief interval when the tubes conduct, C3 charges through the diodes, but when the tubes are cut off, C3 cannot discharge except by leakage. The voltage across C3 is therefore relatively constant. The circuit is initially adjusted to make the voltage across C3 (which is the output) equal to that which normally appears at the centertap between R1 and R2 when there is no error in either phase or velocity.

In the phase-error detector the trapezoid voltage developed from the tone-wheel signal is now fed into the centertap of the network. Since the trapezoid frequency is 240 cps, and the sampling pulses occur at 60 cps, only every 4th trapezoid is used. (In the velocity-error detector the sampling pulses appear at 240 cps, so each cycle of the trapezoid is used. Other than this, the circuits operate identically.) The pulses are used to determine the exact instant at which the trapezoid is sampled, but the relative phase of the trapezoid depends upon the head-wheel position and speed at any instant. Thus, if head-wheel operation is normal, sampling occurs at the center of the slope at a time when the trapezoid voltage is exactly equal to the voltage across C3, so the output remains unchanged. If the head-wheel slows down, thus causing incorrect head-wheel phase, the relative phase of the trapezoid is such that sampling occurs high up on the slope. This makes the plate of diode V1 more positive than the cathode, which is at a potential equal to the voltage across C3, and V1 conducts. Effectively, this increases the error signal in the positive direction, and causes the motor to speed up until the sampling pulse slides down the slope to the center once again. Conversely, if the head wheel should pick up speed, V2 operates, since the sampling occurs at a lower than normal position and reduces the output, which in turn, causes the motor to lose speed until it is again operating correctly.

Chapter 11

VIDEO CIRCUITS

As was the case in the servo systems, certain uncommon circuits appear in the signal channels of both video recorders. In general, these circuits are used to adapt the video signal to the machine's characteristics during recording, to provide cable terminations at the proper impedance and voltage levels, or to alter the signal so that the final output during playback conforms to TV standards. Many of the circuits used in the video system are found in TV studio equipment and industrial devices. A few appear also in the servo systems of the video tape machines.

Clampers

Figure 11-1, part (A), illustrates a simple diode clamper circuit containing a capacitor, resistor and diode. The diode may be either a tube, or one of the semiconductor types. Clampers operate with any waveform, but for convenience we will assume that the input waveform is square, as shown in (*B*) of the figure. With this input, the output is then the waveform at (*C*). Note particularly, that the two waveforms are identical, except for the location of the center axis. The input waveform is centered on the zero-volt line, while the output waveform has a center axis at a negative voltage, −E. Further, the positive peaks of the output never exceed zero volts. The output is said to be clamped at this value, and for this reason the circuit is known as a *positive-peak clamper*. If the center axis is considered as a d-c component, the circuit is referred to as a *negative d-c restorer*, since the output has a negative d-c component not present in the input.

In the circuit shown, the resistor and capacitor are designed to provide a long time constant, and R is usually quite large. The diode is in parallel with the

resistor, and has a very low resistance when conducting. When it is not conducting, the diode may be considered as an open circuit, and the total circuit resistance is that of the resistor alone. Thus, during the nonconducting time, the circuit has a long time constant, but when the diode conducts, its resistance is shunted across the resistor, and the circuit is changed to one with a very short time constant.

Let us assume that the input wave starts at some negative value, which we will call −E. The resistor and capacitor, due to the long time constant, act much

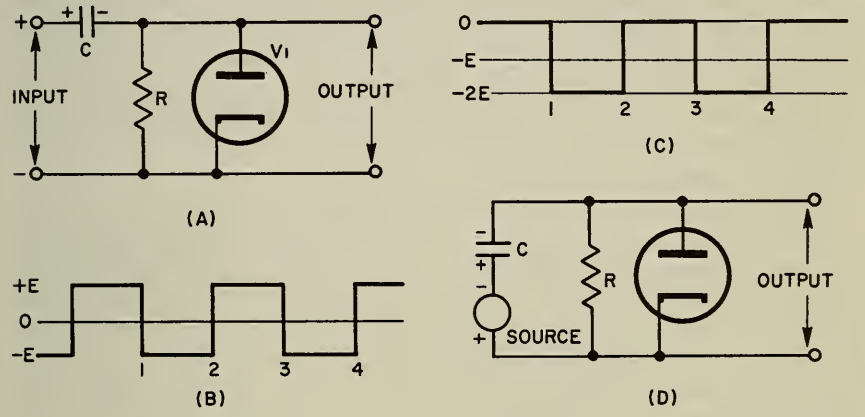


Fig. 11-1. Typical diode-clamper circuit.

as the coupling circuit in the grid of an amplifier, and merely pass the input wave on to the diode. At this time the signal polarity is negative, and the diode appears as an open circuit. The output, as waveform (*C*) indicates, is the same as the input. When the input suddenly reverses polarity, as at position *2* in the input wave, the diode plate becomes positive and the diode starts to conduct. With the diode conducting, the time constant of the circuit is short, and the capacitor charges to the full applied voltage (+E) almost instantly, acquiring the indicated polarity. As soon as the capacitor has been fully charged, the diode stops conducting, for there is now no voltage applied to it. This is seen by considering the input circuit as redrawn in part (D) of Fig. 11-1. The source and the capacitor are in series, but their polarities are opposing one another. Moreover, the capacitor voltage is exactly equal in amplitude to the source, and so their sum is zero. Since there is no voltage across the diode, it cannot conduct. More important, however, is the fact that the output is directly connected across the sum of the two voltages. Thus, the output voltage is also zero, and it remains at this value as long as the source voltage remains at +E, for the capacitor cannot discharge during this interval.

At point *3* in the input wave the signal polarity reverses itself. Considering part (D) of the figure, then, the two voltages add, producing −2E volts across the diode. Since this is negative, the diode does not conduct, and the full value of this voltage, −2E, appears at the output. During the interval from point *3* to point *4* in the wave, the output changes slightly, for the capacitor is now able to discharge through the resistor. But the time constant of the circuit is long and the amount of discharge is negligible. The output for this period is essentially −2E.

At point *4* in the wave, the polarity is again reversed. At this time the capacitor has almost, but not quite, the full charge from the preceding cycle, so only a small voltage is applied to the diode, which then conducts and charges the capacitor back to the full value of +E, again almost instantly. Conditions in the circuit are now identical to those during the interval from *2* to *3*, and the output remains at zero volts. Further reversals of polarity cause the same changes to occur cycle after cycle, with the positive peak held to zero volts, and the negative peak to −2E.

In the event the input voltage amplitude increases, causing the positive portion of the input wave to rise above +E, the first positive going portion of the cycle will once more cause the diode to conduct, and the capacitor charge will be increased to the new, higher value. In turn, this will be exactly equal to the source voltage, and the output will again be held at zero volts for the positive peak. On the other hand, if the input amplitude should decrease so that the positive portion of the input cycle is less than +E, the capacitor charge will be greater than the source voltage for several cycles, causing the output to be negative during the positive-going portions. This condition exists for only a few cycles, however, for the capacitor starts to discharge through the resistor, and continues to discharge until, after several cycles, the capacitor voltage is equal to the new source voltage, after which the clamping action continues as if there had been no change, and the positive peaks are maintained at zero volts.

A similar circuit is easily constructed for clamping the negative peaks of a wave to zero volts. In this application it is only necessary to reverse the diode so that it conducts on negative-going portions of the input wave. Under these circumstances, the charge on the capacitor is reversed, and the output positive peak is permitted to rise to +2E while the negative peak stays at zero volts. Obviously, this would be a negative peak clamper, or, if the d-c axis is considered, a positive d-c restorer.

Additional clamping circuits may be designed to clamp either extreme of a wave to voltages other than zero. This is done by inserting a battery (actually, a voltage from the power supply is used) between the diode and ground. For example, suppose that a battery were inserted between the cathode of the diode and the ground connection in Fig. 11-1, part (A), so that the cathode was 2 volts positive with respect to ground. The diode would then conduct only when the input value exceeded the battery voltage. The positive peaks would therefore be clamped to +2 volts. Similarly, if the battery polarity is reversed,

clamping occurs at −2 volts. In either case, with the circuit shown, it is the positive peaks of the wave that are clamped to the battery voltage value. To sum up, clamping circuits may be designed to provide clamping of either extremity at any desired voltage.

In place of the battery, a series of pulses may be applied to the diode circuits. Clamping action will then occur only during the time intervals specified by the

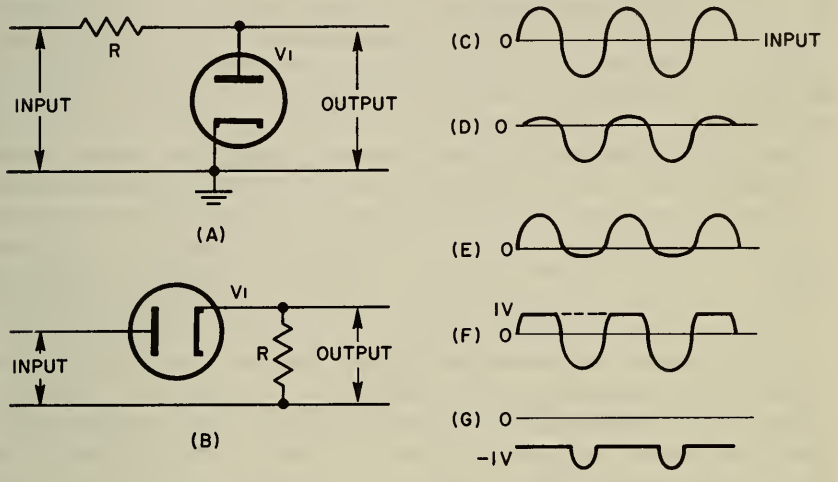


Fig. 11-2. (A) Shunt clipper. (B) Series clipper.

pulses. Such a system is called a *keyed clamp*, and is often used in TV systems to clamp signals that occur at specific time intervals, while no clamping is provided at other times.

In passing, it is of interest to note that clamping action may also be developed in the grid circuit of an amplifier by permitting the grid to act as a diode plate. Output, instead of being taken from the grid connection, is taken from the plate circuit of the tube, and the output wave is clamped to some value of voltage in the plate-supply circuit.

If clamps are to be effective, coupling capacitors cannot be used following the clamper circuit, for they remove the d-c component that the clamper has inserted into the signal, and restore the center axis to zero volts.

Clippers

Figure 11-2, parts (A) and (B), illustrate diode clipping circuits. The circuit at (A) is known as a *shunt clipper* while that at (B) is a *series clipper*. Both circuits act similarly, and are based on the fact that a diode has a small resistance when conducting, but appears as an open circuit when not conducting.

The resistor in the circuit is large compared to the conducting resistance of the diode.

Suppose that a sine wave [waveform (*C*)] is fed into the shunt clipper. At any time when the input voltage is positive on the plate of the diode, it conducts, and appears as a very small resistance. During the positive portion of the cycle, then, the diode is conducting, and the circuit is effectively a voltage divider composed of the diode and the resistor in series across the input. In this divider, the resistor is much larger than the diode. Consequently, almost all the voltage is dropped across the resistor and practically none across the diode. The output is taken across the diode, and is therefore zero volts for all practical purposes. Actually, as waveform (*D*) indicates, the output is not quite zero, since the diode resistance itself is not zero.

During the negative half cycle the polarity of the input is reversed and the diode plate is made negative, causing the diode to appear as an open circuit, or, if a semiconductor type diode is used, as an extremely large resistance, much larger than the resistor in the circuit. In either event, the circuit once more appears as a voltage divider, but now the voltage is dropped across the diode instead of the resistor. Since the output connection is taken across the diode, the output voltage is practically equal to the input voltage, as shown by waveform (*D*). Because the positive half cycles are removed from the input wave by the circuit it is known as a *positive clipper.*

Reversing the diode in Fig. 11-2, part (A), causes clipping action to occur during the negative half cycles. The action of the circuit is identical to that described above, except that the diode now conducts when its cathode is made negative, and does not conduct when the cathode is positive. The output waveform under these conditions is shown at (*E*), and the circuit is known as a *negative clipper.*

If a voltage source is placed between the diode and ground, the clipping action may be made to occur at a level other than zero volts. To illustrate, if the cathode of the clipper in part (A) of Fig. 11-2 is made positive by 1 volt, the diode will not conduct until the input signal exceeds this value. The positive peaks will then be sliced off at the 1-volt level, producing waveform (*F*). Reversing the polarity of the voltage between cathode and ground (but not the diode itself), causes clipping to occur at −1 volt, giving rise to waveform (*G*). Similar clipping may be obtained for the negative peaks by reversing the diode and inserting a bias voltage between plate and ground.

The series diode clipper acts in much the same manner as its shunt cousin. When the positive half cycle of the input wave is applied to the circuit, the diode conducts, and appears as a very small resistance compared to the resistor. The circuit is once again a voltage divider, but this time the output is taken across the resistor, and practically the entire input voltage appears at the output. During the negative half cycle, the diode does not conduct, and appears as a much larger resistance than R, causing all the voltage to be dropped across the diode itself, and none across the resistor. The output at this time is therefore zero, and the output waveform is as shown at (*E*).

Reversing the diode in the series clipper produces output waveform (*D*), since the diode conducts during the negative half cycles, but is an open circuit for the positive portions. As with the shunt clippers, voltage sources may be inserted into the circuit to provide clipping at levels other than 0 volts. For either type of diode clipper, any waveform may be fed into the circuit and clipped at a desired level.

Amplifier input circuits may also be used to clip the peaks of waveforms. For example, if an amplifier is biased at cutoff, negative-going portions of the input signal will not cause any changes in plate current, and they do not appear in the output. Biasing a tube at saturation, similarly causes the positive-going portions of a signal to be removed. If the bias is located at some point other than saturation or cutoff, any signals exceeding these limits will be clipped. Both positive and negative peaks of a waveform may be sliced off in this manner by using normal bias but overdriving the grid circuit so that the signal peaks exceed both saturation and cutoff.

Cathode Follower

The cathode follower, shown in Fig. 11-3, part (A), is a special type of amplifier in which the output is taken from the cathode circuit rather than the plate. The input, as indicated, is applied between grid and ground, and is equal to the sum of e_{gk} and e_k, as these two voltages are in series between the grid and ground. The cathode voltage, e_k, is the output, and it must be lower in amplitude than e_{in}. The cathode follower therefore cannot provide voltage amplification, since the maximum value of the cathode voltage is the input signal voltage. In practice, the output voltage of the cathode follower is usually much less than the input, although in some instances it may be almost equal to the input. Output signal power, however, may be substantially greater than the input signal power, so the cathode follower acts as a power amplifier. In the circuit illustrated, R3 is used to drop the supply voltage to a more reasonable value for use in the circuit, and C1 bypasses any signals at the plate. In most instances C1 is fairly large, 20 μf or more, to ensure that no signals get into the power supply from the plate circuit. R1 is a standard grid resistor, and C2 acts as a coupling capacitor.

Because the output is taken from the cathode circuit, it is not possible to bypass the cathode resistor. Accordingly, the cathode follower supplies its own negative feedback. In turn, this provides more linear, distortion-free operation, makes the output more stable, or free from the effects of supply voltage variations, and widens the bandwidth of the circuit. The circuit configuration also causes a reduction in the input capacitance of the stage, a condition that widens the bandwidth even more, making the cathode follower suitable for use with high-frequency signals.

The cathode resistor, R2 acts both as the load on the tube and as the cathode-bias resistor. With no input signal, plate current through R2 produces the bias

voltage. When a signal is applied, plate current variations cause the voltage across R2 to vary in accordance with the signal changes. If the input goes positive, plate current increases, producing a higher drop across R2. Negative-going input signals reduce the plate current, and so cause a smaller drop across R2.

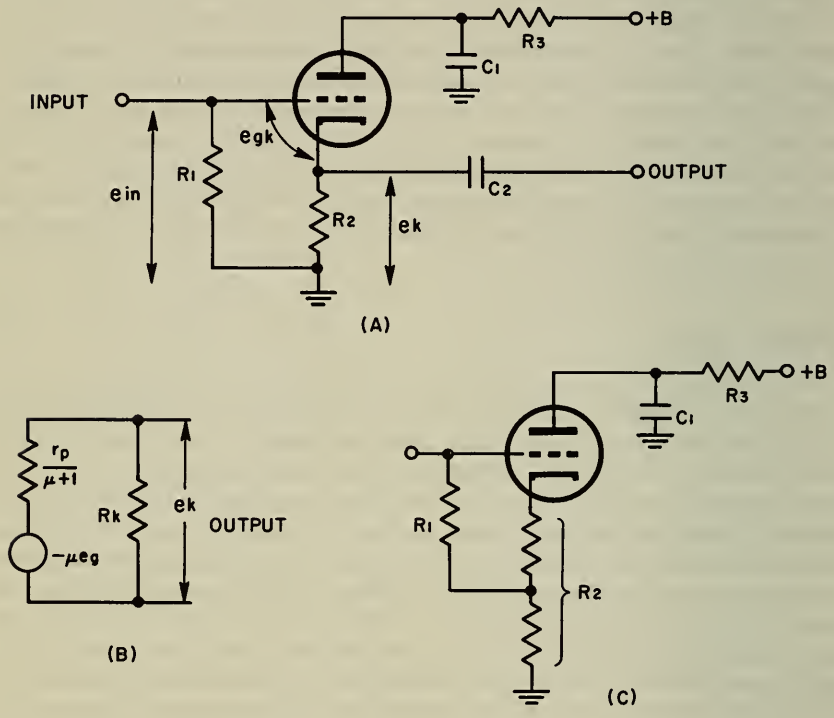


Fig. 11-3. Typical cathode follower.

But the voltage across R2 is the output voltage, and this increases with positive signals and decreases with negative signals. In other words, the output is in phase with the input.

Cathode-follower input impedances are high, since the input circuit is much the same as a conventional amplifier. On the other hand, the output impedance of the cathode follower is quite low, and may be found from the equivalent circuit illustrated in Fig. 11-3, part (B). Looking back from the output, the impedance seen is the parallel combination of the cathode resistor, R_k, and the equivalent tube plate resistance, $r_p(\mu + 1)$. If μ is large, the equivalent plate resistance is approximately equal to the reciprocal of the transconductance. In general, large values of transconductance reduce the output impedance of the

circuit. Cathode followers with output impedances of 100 ohms or less are not uncommon.

Because the cathode follower provides a low-output impedance, it is often used to feed low-impedance cables, and transmission lines which must be matched at the sending end. In this application the low impedance helps to minimize the effect of the cable capacitance that shunts the circuit. Further, the cathode follower may be used as an impedance-matching device in circuits where transformers are either too expensive, or might create distortion. It may also be used with high-impedance loads that tend to vary somewhat, as these variations will not affect the output impedance of the circuit.

One defect of the simple cathode-follower circuit is an inability to handle large amplitude signals without creating distortion. Basically, the distortion is a form of negative peak clipping, for as the signal voltage becomes more negative, the tube approaches cutoff. Positive-going signals, conversely, do not drive the tube to saturation until they are quite large, mainly because any increase in the grid voltage also increases the cathode voltage, making the difference between them increase more slowly. To overcome this defect, the grid resistor is returned to a tap on R2 rather than to ground, as shown in Fig. 11-3, part (C). Bias is reduced in this manner, and the tube can accommodate larger negative input signals. With this arrangement, output may be taken at the tap point and the upper portion of R2 may then be bypassed or, if desired, the output may be taken from the top of R2, in which case no bypassing is possible.

Cascode Amplifier

The cascode-amplifier circuit illustrated in Fig. 11-4 is one of a group of amplifiers in which two tubes are combined into a single stage to provide certain advantages over more conventional single-tube amplifiers. In the case of the cascode amplifier, the main advantage lies in a lower noise level for roughly the same amount of amplification as a single-tube circuit. Generally, the cascode amplifier is used in circuits where the signal level is quite low, and its relative freedom from noise is therefore an important consideration.

In the circuit shown, signals are fed into the first tube, V2, and output is taken from the plate circuit of the second amplifier. The tubes are effectively in series with each other across the B supply and the plate resistance of V1, together with R4, acts as the load for V2. Simultaneously, V2 appears as a resistance between the cathode of V1 and ground. Although the cathode of V1 is at a fairly high potential above ground, the grid of this tube is connected to the bottom of R4, establishing the drop across this resistor as the bias on V1. Note that C3 bypasses any signals that might appear at the grid of V1, and maintains the grid at the d-c average value of plate voltage for V2. Resistor R3 is inserted for isolation purposes to prevent C3 from short-circuiting signals at the plate of V2, to ground. Bias for V2 is obtained across R5, bypassed by C2.

As the grid voltage on V2 changes in accordance with the input signal, the

plate current through the first tube changes, increasing when the signal voltage increases, and *vice versa.* But the plate current in V2 is also the current in R4, so the voltage across this resistor also varies in accordance with the input signal. Now, the grid of V1 is connected to the lower end of R4, and due to the action of R3 and C3, is at a fixed d-c potential. Any change in the voltage across R4 then appears as a change in the voltage at the cathode of V1. Since the input voltage to an amplifier is not the voltage applied to the grid, but rather the

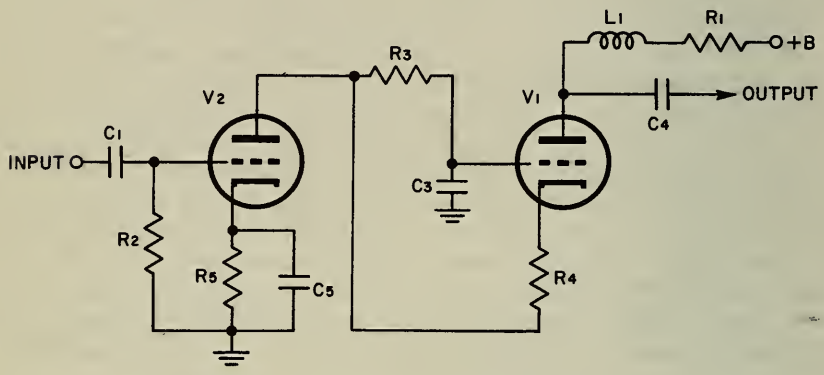


Fig. 11-4. Diagram of a cascode amplifier circuit.

difference between grid and cathode voltages, the varying voltage across R4 is the input voltage to V1. This tube now acts as an amplifier, with R1 as its load. The peaking coil, L1, is used to improve the high-frequency response of the system, and C4 acts as an output coupling capacitor.

In almost all applications, the cascode amplifier uses two identical triodes. The characteristic curves of the combined tubes appear similar to those of a pentode, but they are more linear, particularly at the low current end.

The amount of amplification provided by V2 is quite small because it effectively operates into a low-load resistance which, neglecting R4, is roughly equal to the sum of the plate resistance of V1 and R1, divided by the μ of V1. On the other hand, V1, since it is more conventional, provides a large amount of amplification. In fact, for the overall circuit, V1 provides almost all the amplification. However, V2, because it is the first stage in what is essentially a cascaded amplifier chain, produces almost all the noise generated in the circuit. Due to the low amplification of V2, this noise tends to be less than that provided by a single-tube amplifier. Furthermore, although V2 provides little amplification, its output is nevertheless greater than its input, and when this is amplified by V1, the resulting overall amplification of the combined tubes exceeds that of a single-tube stage. Finally, the coupling arrangement between the tubes causes the

cutoff characteristics of both tubes to be combined. In turn, this reduces the possibility of overloading the stage and creating distortion.

Series Amplifier

The series amplifier of Fig. 11-5 appears, at first glance, to be substantially similar to the cascode circuit of the preceding section. Note however, that the output is taken from the cathode of V1 rather than the plate. Because of this, both the output impedance and the available amplification are quite low. Bias for the tubes is obtained in the same manner as in the cascode circuit, and C3 and R3 perform identical functions in this circuit as in the other. The plate of V1 is bypassed to ground, so the load on this tube, neglecting R4, is the dynamic plate resistance of V2. Similarly, the load on V2 is, for all practical purposes, the dynamic plate resistance of V1.

Operation of the series amplifier resembles that of the cascode amplifier, up to a point. For instance, signals are fed into V2, which acts as a straightforward amplifier. Increases in signal voltage cause the plate current to increase, and in

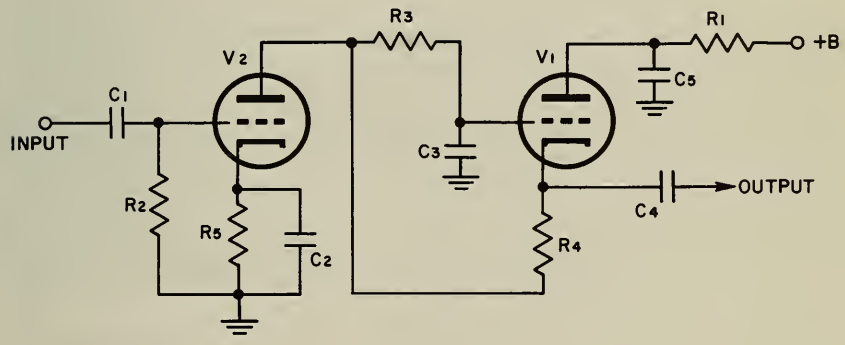


Fig. 11-5. Schematic diagram of a series amplifier.

turn increase the cathode voltage on V1. This is the equivalent of making the grid of V1 negative with respect to its cathode, so the input voltages applied to V1 and V2 are 180° out of phase with each other. The plate resistance of a tube is generally constant only over a small, or limited, range of input signals. For large signals, the dynamic plate resistance of a tube increases as the grid becomes more negative, and *vice versa.* Thus, in the series amplifier, when the plate resistance of V2 tends to increase, that of V1 decreases. Since V1 acts as the load on V2, the overall circuit resistance tends to remain constant, giving rise to a very linear relationship between input and output. This is true also of the cascode amplifier, but since that circuit is usually employed with small signals,

linearity is not too important. For the series amplifier, which is used with large signals, the linear relationship reduces distortion substantially.

Mathematical analysis of the series amplifier indicates that for minimum distortion the values of R4 and the external load with which the circuit operates, are interrelated. But in order to provide proper bias for V1, R4 cannot be large, particularly if tubes with high plate currents are used. Under these circumstances, the circuit provides a very low output impedance, usually less than 50 ohms. With such a small external load, the amplification produced by the circuit is less than unity, making it similar to the cathode follower in this respect. However, the series amplifier does provide less distortion and lower output impedances than the cathode follower, making the circuit useful for feeding low-impedance cables.

Cathode-Anode Follower

Another form of series amplifier is illustrated in Fig. 11-6. In this arrangement, the signal is fed into the upper tube, V1, and output is taken from the

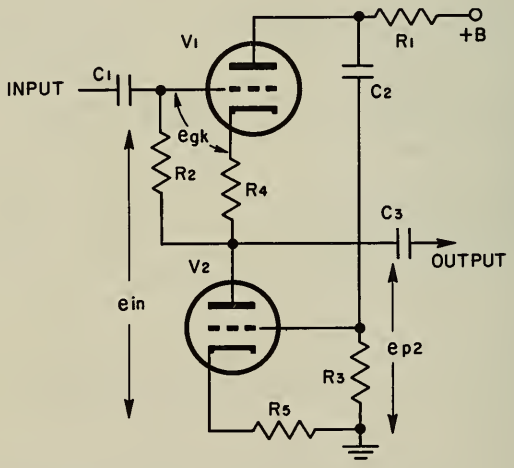


Fig. 11-6. Typical cathode-anode follower.

plate circuit of V2. The circuit may be considered as a cathode follower with V2 forming part of the cathode resistance. The grid of V1 is returned to a tap point on this resistance, in a manner similar to that shown in Fig. 11-3, part (C), but it must be remembered that in the cathode-anode follower the tap point will vary as the plate resistance of V2 varies. The cathode-anode follower has characteristics similar to the series amplifier, and provides low distortion, low output impedance and linear operation.

Signals are fed into the circuit between the grid of V1 and ground, as in the conventional cathode follower, so that the input is equal to the sum of e_{gk} and, in this circuit, e_{p2}, the signal voltage on the plate of V2. Obviously, therefore, the output, which is also e_{p2}, cannot exceed the input and the amplification is less than unity. Bias for V2 is provided by R5, unbypassed to provide some feedback for the lower tube. Bias for V1 is obtained by the d-c drop across R4.

In addition to acting as a cathode follower, V1 also supplies an additional output through its plate circuit. This output signal, inverted by the amplifier action of V1, is then coupled through C2 and R3 to the grid of V2 where it is amplified and inverted once more. Having gone through two inversions, the amplified signal at the plate of V2 is in phase with the cathode follower output from V1. The output is the voltage across V2, and therefore contains two components, one from V1, the other from V2, hence the name, *cathode-anode follower.*

As in the series amplifier, the two grids are 180° out of phase with one another, so any variations in the plate resistance of the tubes are in opposite directions, causing the overall circuit resistance to be relatively constant. Use of the lower tube, V2, as part of the cathode resistance of the cathode-follower circuit, permits large signals to be handled with even less distortion than that produced by a cathode follower with tapped cathode resistor.

The output impedance of the cathode-anode follower depends upon the value of R1 and the transconductance and amplification factors of the tubes used. For large signals, the tubes chosen are usually those with high plate currents and relatively small values of μ. This being so, the value of R1 itself must be kept small to prevent dropping the supply voltage to too low a level. In turn, this causes the output impedance to be very low, in the vicinity of 30 ohms, or so. As with the series amplifier, the cathode-anode follower is well suited to driving low-impedance cables. It may also be used for multiple-load connections if the combined load impedance is high enough to be neglected.

R-F Multivibrator

Figure 11-7 is the circuit diagram of the r-f multivibrator used in the Ampex monochrome recorder to provide the modulated recording signal. The circuit is basically a straightforward high-frequency multivibrator with a free-running frequency in the vicinity of 5.25 mc. To obtain this high-frequency, the R-C time constants of the grid circuits must be made quite small, and for this reason the grid and plate resistors, as well as the coupling capacitors, have the low values indicated. An interesting feature of the circuit is the lack of screen bypass capacitors. At the frequencies employed in the circuit, such bypassing, in conjunction with the grid-to-screen capacitance inside the tube, would short-circuit the output of the opposite stage.

The output of the multivibrator is taken from both plates by connecting the primary of a transformer between them. Capacitor C3 is used to prevent the d-c potentials of the tubes from affecting one another. Also, note that the trans-

former primary is connected at the junction between the two resistors in each plate circuit. Only 270 ohms appears between the supply voltage and the transformer connection, effectively making the tap point appear at a low a-c potential. Output connections are made to the secondary of the transformer.

In any multivibrator, changing the grid voltage alters the timing of the output, simply because the grid capacitor must now discharge to a different value before

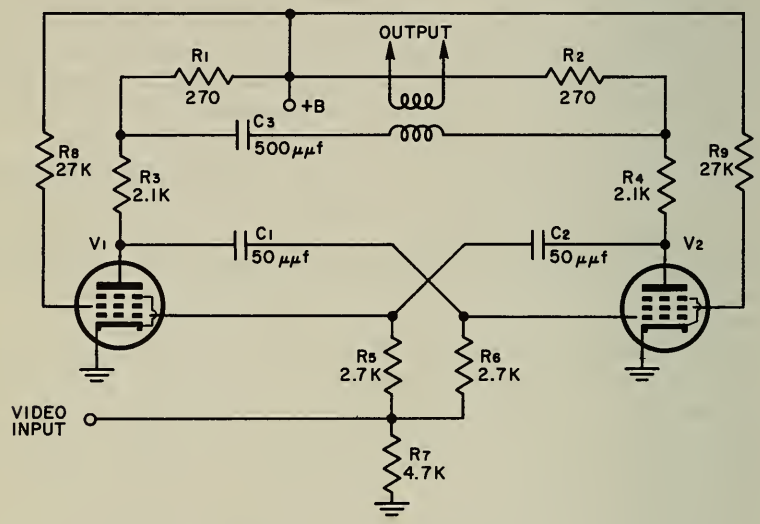


Fig. 11-7. Ampex r-f multivibrator.

the circuit can be made to trigger. In general, if the grid is made less negative, the time required for the capacitor to discharge to a given point is lowered, and the frequency is increased. Conversely, if the grid voltage is made more negative, the capacitor takes a longer time to discharge to the same fixed point, and the frequency goes down. We have then a basic method of creating fm, for if an alternating signal is applied to the grids of the multivibrator, the output frequency will shift up and down in accordance with the voltage variations. In the Ampex system, the video signal is fed into both grids simultaneously. The 2700-ohm resistors are used to provide isolation between the two tubes. As the video signal varies, it changes the grid voltages and the frequency is altered. The polarity of the signal is important in this application, and peak-of-sync is made negative, with white level positive. Thus, during the sync period, the multivibrator frequency is driven down to 4.75 mc, while white-level signals cause an increase in frequency to 6.25 mc. Inasmuch as the peak-of-sync is clamped to a fixed voltage before entering the circuit, the equivalent frequency produced by peak-of-sync appears to be clamped to 4.75 mc.

Although the circuit is basically a multivibrator, some video information will be passed through the tubes to the plate circuits. Any such feed-through is cancelled at the transformer primary, since both ends of the primary would see the same polarity signal at the same time.

Reactance Tubes

A typical reactance-tube circuit operating with an oscillator is illustrated in Fig. 11-8, part (A). The purpose of the reactance tube is to alter the oscillator frequency in accordance with modulating or control signals, and to this extent the reactance tube appears, as its name implies, either as an inductive or capacitive reactance across the oscillator tank. In the circuit shown, the oscillator is enclosed in dotted lines, and the reactance tube is to the left of this section. Capacitor C3 is used to block dc between the oscillator tank and the plate of the reactance tube. It is sufficiently large to be neglected.

Consider first the oscillator. When it is operating, a sinusoidal voltage exists across the tank circuit. The same voltage, called e_s for convenience, is applied

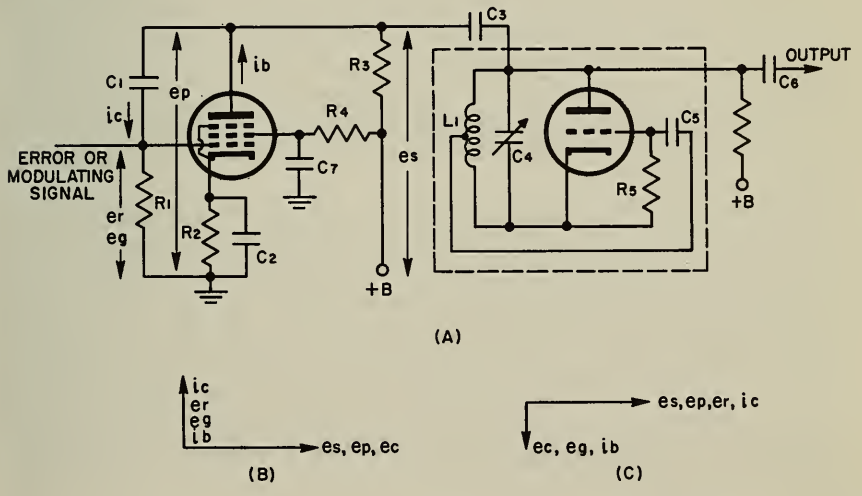


Fig. 11-8. Schematic diagram of a reactance-tube oscillator.

across both the reactance tube and the series circuit consisting of C1 and R1, since both these paths are in parallel with the tank. Thus, in the phasor diagram (part B of the figure), e_s and e_p (the tube plate voltage), are shown in phase with each other. In a typical reactance tube circuit, the value of C1 is chosen so that it has a reactance at least five times as great as the resistance of R1 at the

operating frequency. For this reason, the series branch of R1-C1 is practically all capacitive reactance, and the voltage drop across C1 appears to be in phase with e_s. In a capacitive circuit, however, the current leads the voltage by 90°, and so, in the phasor diagram, i_c is shown in this position. But C1 and R1 are in series, so the current through C1 is the same as the current through R1. Further, for a resistor, the voltage across it is in phase with the current through it. The voltage across R1 is therefore 90° ahead of both the capacitor voltage and the applied signal voltage. Also, the voltage across R1 appears between grid and ground, and is, therefore, the input grid voltage to the reactance tube. But, in any tube, plate current and grid voltage are in phase, so the plate current appears in the same phasor position as i_c. This is 90° ahead of the plate voltage, e_s. This being so, the tube resembles a capacitor, since its internal current leads the voltage across it by 90°.

An interesting condition occurs if the positions of R1 and C1 are interchanged, and R1 is made very large compared to the reactance of C1. The same applied voltage now causes the bulk of the drop in the R-C branch to appear across the resistor, and the current through that branch is in phase with e_s. The capacitor is in series with R1, so the voltage across its terminals lags the applied voltage, e_s, by 90°. Again, the voltage across C1 is the voltage between grid and cathode, or, in other words, the grid voltage. In Fig. 11-8, part C, then, the phasor diagram indicates a grid voltage lagging the applied voltage by 90°. Once more, the plate current is in phase with the grid voltage, so it lags the plate voltage by 90°. Now, a device in which the current lags the voltage across it, is, to all intents and purposes, an inductance. The circuit therefore provides an equivalent inductive reactance.

In either circuit, it is desirable to have the value of equivalent reactance variable. In the reactance tube this is done quite simply, for the magnitude of the equivalent reactance depends upon the transconductance of the tube. In turn, this depends upon the control grid voltage. Making the grid more negative decreases the current and the effective reactance. An increase in grid voltage causes an opposite effect. If a d-c error signal is inserted into the grid of the reactance tube, the oscillator frequency may be made to vary with the amount of error. If an audio or video signal is injected into the grid, the oscillator frequency will be altered many times a second, in accordance with the size and the rate of change of the input signal.

Ampex R-F Gate

Before discussing the circuit of the r-f gate used in the Ampex video recorder during playback, we must first examine briefly the operation of a pentode. Neglecting for a moment, the effect of the screen and suppressor, making the control grid exceedingly negative stops plate current from passing through the tube. Conversely, if the grid is made positive, or perhaps, less negative, current once more exists in the tube. Suppose now, that the grid voltage is fixed so

that plate current is passed. Suppose further, that the suppressor is now made negative. Electrons in the stream approaching the plate see the negative field produced by the suppressor, and are repelled. If the suppressor is only slightly negative, quite a few of the electrons may get through. There is, however, a value of negative voltage that may be applied to the suppressor that will completely stop the plate current, *regardless of control-grid voltage.* It is this action of the suppressor that is used in gating circuits. Instead of connecting the sup-

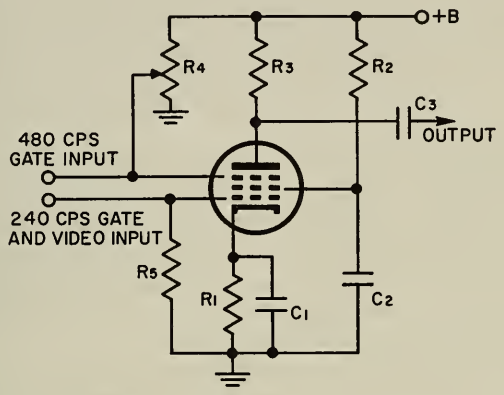


Fig. 11-9. A coincidence gate: a modified version of the Ampex r-f gate. *After Ampex.*

pressor to cathode or ground, it is connected to a source of "gating pulses" that appear as a repetitive rectangular wave. Generally, the gating wave has a relatively high peak-to-peak amplitude. During the negative-going portion of the wave, the suppressor completely cuts off the tube. Conversely, during the positive portion, the tube conducts. The suppressor pulses therefore act as a *gate*, opening and closing the path of plate current through the tube. Signals on the grid pass through the tube only when the gate is open.

Gating may also be applied to triodes. In this case, the gating wave is applied to the cathode or grid. As with the pentode, the pulses open and close the plate-current circuit, and signals reach the plate only when the gating wave permits plate current to appear in the tube.

The circuit of the Ampex r-f gate is shown in modified form in Fig. 11-9. Peaking coils, isolation resistors, and coupling networks have been eliminated for convenience. In this circuit, R1 and C1 provide normal cathode bias when the gate is open (in circuit terminology, the gate is open when the tube conducts). R2 provides screen voltage, and the screen is bypassed to ground through C2. The control grid circuit is returned to ground through R5, and the suppressor is tied to ground through R4. One end of R4 is connected to the B supply to provide an operating bias for the suppressor. R3 acts as the plate load, and C3 is

the output-coupling capacitor. Three signals are fed into the gate: a 480-cps gating pulse to the suppressor, the video signal, and a 240-cps gating wave (the get-ready signal) to the grid.

Let us first consider the action in the control grid. Ignore for the moment, the video signal fed into this electrode. As indicated above, the tube cannot conduct if the grid is beyond cutoff. Thus, regardless of any other conditions in the circuit, if the 240-cps gating wave, which has a center axis at 0 volts, is negative, the grid voltage is far beyond cutoff, and the tube is dead. Now, the 240-cps pulse applied to the grid is roughly square, having equal positive and negative half cycles, so the grid is held beyond cutoff for a period of time equal to one half cycle of the grid gating wave. During the other half cycle, when the grid is positive, plate current may pass through the tube, provided the suppressor circuit permits it to do so.

The video signal is also applied to the grid. However, it merely adds to the gating wave already present, and has no effect on the tube action unless plate current is actually flowing. Essentially then, the video signal uses the grid gating wave as a zero axis. During the negative half cycles of the gating wave this is of no consequence as the tube is off in any event. During the positive portion of the grid gating wave the video signal is present at the grid with the correct bias, so that it may be amplified if the gate is open.

While this action occurs in the control grid, the suppressor receives a 480-cps square wave that alternately drives it negative and positive. The zero axis of this gating wave is the potential applied to the suppressor through R4. When the suppressor is negative, regardless of grid action, the tube is cut off. When the suppressor is positive, plate current will exist only if the control grid permits. Thus, for the video signal to pass through the gate, both control grid and suppressor must be positive. Now, the timing of the system is such that the control grid is driven positive by its gating wave at a somewhat earlier time than the suppressor. When the suppressor does become positive, plate current starts in the tube and continues for as long as the suppressor is positive. During this period the video signal on the grid is passed through the tube and amplified. Eventually however, the suppressor wave again reverts to a negative value, and plate current ceases, although the grid is still positive. A short time later, the grid is driven negative by its gating voltage, and, although the suppressor becomes positive shortly after this, the negative grid signal keeps the gate closed. When the two gating pulses again coincide in the positive direction, the video signal is once more passed through the tube. Since the two gating signals must coincide in direction, circuits of this type are often known as *coincidence tubes*, or coincidence gates.

RCA Diode Gates

Gating circuits may also be designed with one or more diodes as the switching device, rather than a triode or multi-element tube. The simplest diode gate is

formed by a single diode which is fed with both the signal to be gated, and a gating wave. The purpose of the gating wave is to bias the diode in the reverse direction so that conduction cannot occur, regardless of signal polarity, during the "off" time. Diodes biased in this manner are said to be *back-biased.* In most instances, diode gates are operated with rectangular gating waves having fairly

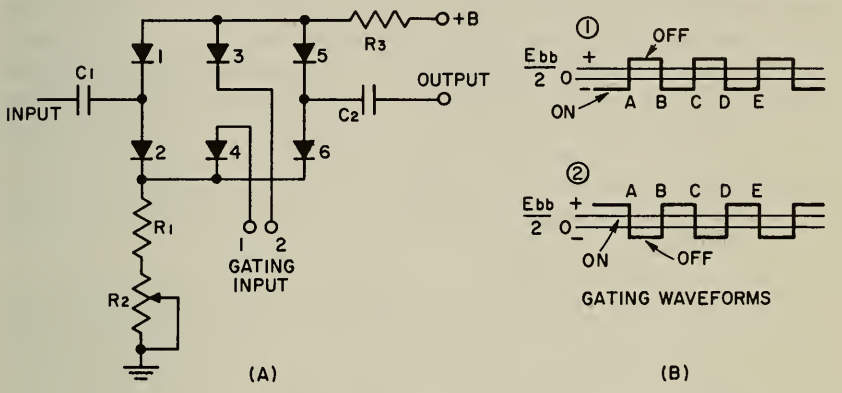


Fig. 11-10. The six-diode gate. *After RCA.*

high peak amplitudes. Gating circuits with a single diode are usually restricted to passing pulses of a single polarity, and are known as unidirectional gates.

For use with signals that alternate in polarity, a bidirectional gate may be constructed with a minimum of two diodes. These are connected in such a manner that back-bias is present on both diodes simultaneously when the gate is closed, requiring two gating signals, one the inverse of the other. Gates of this type, although fairly simple to construct, suffer from sensitivity to any unbalance in the gating waveform. In addition, the capacitance across the diodes may cause some signal to be passed through the gate even when it is supposedly closed. To eliminate these conditions, gating circuits with four or six diodes are used. In addition to two gating waves, these multidiode gates also require a polarizing voltage, but this is easily obtained from the B supply.

Diode gates cannot provide the amplification of a multigrid tube. In fact, they cause a loss in signal strength between the gate input and output. In this respect, a diode gating circuit with six diodes provides less loss than one with only four diodes, and so the former is more applicable to working with low-level signals, particularly if the signal-to-noise ratio must be kept high.

The circuit of Fig. 11-10, part (A), illustrates the six-diode gate used in the RCA switchers. Only a single gate is shown, inasmuch as they are all the same. The timing of the gates is controlled by the multivibrators that generate the gating waves. In turn, the multivibrators are synchronized to the head-wheel

pulses, so gating occurs at the appropriate intervals. Part (B) of Fig. 11-10 illustrates the control, or gating, waves that are applied to the gates from the multivibrators. Waveform 1 is applied to diode 4, while wave 2 is fed into diode 3. Note that the gating waves are the inverse of each other.

Assume for the moment, that the gating waves and the input signal are all disconnected from the circuit. Diodes 1 and 2 are connected between the B supply and ground in a series arrangement. Similarly, diodes 5 and 6 are connected across the supply. Due to the polarity of the diodes and the supply voltage, all four diodes are able to conduct, and current flows through both branches. The resistance of the diodes during conduction is quite low, causing the supply voltage to be dropped across resistors R1, R2, and R3. R2 is made adjustable so that the voltage at the junction of R1 and the diode circuit, is slightly less than half the supply voltage. Due to the small drop across the diodes themselves, the voltage at the junction of R3 and the diodes is slightly higher than half the supply voltage.

Let us now apply a video signal to the gate input through C1. In the absence of any gating waves, the injection of a relatively small voltage between diodes 1 and 2 cannot overcome the potentials developed by the supply voltage, and the diodes continue to conduct. This being so, the signal is transmitted through diodes 1 and 2 as if they did not exist. Since identical conditions prevail in the branch containing diodes 5 and 6, the signal is passed through these diodes also, and on to the output through C2. Both C1 and C2 are placed in the circuit to prevent the d-c potentials on the diodes from being affected by the source or load.

We may now consider the gating waves. The *on* position of each wave must be of sufficient amplitude to ensure that diodes 3 and 4 are back-biased, and therefore not conducting. For diode 3, the gating wave must be more positive than the voltage at the junction of R3 and the diodes, which is approximately half the supply voltage. For diode 4, the gating wave must be more negative than the voltage at the top of R1, also approximately half the supply voltage. Under these circumstances, diodes 1, 2, 5, and 6 operate as indicated previously, during the time intervals from *B* to *C*, *D* to *E*, and so on, in the gating waves.

At point *C* in the gating waves, the polarity is suddenly switched, and diodes 3 and 4 are no longer back-biased. Since both of these diodes now conduct, and provide a low resistance path for current, the voltages at the junctions of the resistors and the diode circuit are both altered. At the top of the gate (the junction of R3 and the diodes) the gating wave causes the voltage to become negative, while the junction of R1 and the diodes is driven positive. Essentially, the junction point voltages are equal to the *off* amplitude of the gating waves. This back-biases diodes 1, 2, 5, and 6, and prevents them from transmitting the signal through the gate. At point *D* in the gating wave, the polarity is once more reversed, diodes 3 and 4 again become back-biased, and the gate is open. At point *E*, gating wave reversal again closes the gate and prevents transmission. The action continues in this manner, with the gating waves alternately back-biasing the two and four diode combinations.

Delay Lines

Fundamentally, a delay line is a piece of transmission line specially engineered to provide a time lapse between input and output. That such a time lapse exists is easily noted if we remember that radio waves travel at a rate of 186,000 miles per second in air. This is roughly the same as saying that it takes 5 microseconds for a radio wave to travel one mile. If the wave is fed through a transmission line or cable rather than air, the length of the path may be fixed, and the time required for the wave to travel the length of the line, calculated. To obtain reasonable delays in this manner it would seem that long lines are

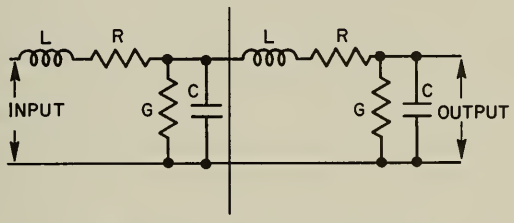


Fig. 11-11. Sections of a delay line.

necessary, and clearly, this would be next to impossible. Fortunately, transmission lines may be simulated by circuit components, and an equivalent line may be constructed in a small physical space.

Externally, a transmission line or cable appears to be a pair of conductors separated by an insulator. For example, a simple transmission line might be composed of two parallel wires separated by air. The wires themselves contain resistance. What is more, they also contain a small amount of inductance, for inductance is a property of a circuit that is not so much associated with a coil, as it is with a conductor. It is true, of course, that the inductance in a straight length of wire is small, but nevertheless, it is present. Present also in the transmission line, is shunt capacitance between the two conductors. There is also shunt conductance between the two wires due to the fact that insulation, including air, is not perfect, and some leakage current flows between the conductors.

In a transmission line, these four circuit elements exist in a distributed form along the length of the line. In other words, a little of each appears at every point on the line. The study of line operations is simplified greatly, however, if the line is assumed to have lumped constants, that is, each element appearing at only one position on the line. Actually, this is too much of a simplification, so a compromise is made. The line is assumed to be composed of sections, each 1 meter long, and within each section the total inductance is considered as a single unit, as are the other circuit constants. Thus in Fig. 11-11, two sections of a line are shown, each indicating the line constants by a single symbol.

In transmission line theory it is convenient to work with a *lossless* line, one in which no power losses due to the resistance or conductance occur. Although such a line cannot be built, it may be approximated, and lines exist in which these two components may be considered negligible. The line sections then contain only inductance and capacitance. Now, let us assume that such a line is constructed and permitted to stretch to infinity. Let us also feed a signal into the line from a generator, and measure both the generator current and voltage. The ratio of the measured voltage to the measured current is E/I, which is an impedance. This is called the *characteristic* impedance of the line.

It is apparent that a useful line cannot extend to infinity in length. As a practical matter, though, it has been found that if a line of finite length is terminated at its far end by an impedance equal to its characteristic impedance, the generator cannot tell the difference, and acts as if it were feeding an infinitely long line. Thus, a short line may be made to resemble an infinite line. Mathematical analysis of such a line indicates that the characteristic impedance is $\sqrt{L/C}$, where L is the inductance of a section, and C the shunt capacitance of a section. Further mathematical analysis shows that for an infinite lossless line (one terminated in its characteristic impedance), the velocity with which the signal travels down the line is a function of the section constants, and is equal to $1/\sqrt{LC}$. But velocity is, for all practical purposes, distance divided by time. If a single section, 1 meter long, is considered, then the time required for a signal to travel from one end to the other is given by the expression $\sqrt{LC}$. To illustrate, a line having 50 microhenries inductance per meter, and 100 micromicrofarads capacity per meter, provides a delay of 0.07 microsecond. If the line is made 100 meters long, it contains 100 sections, and the delay over the entire line is then 7 microseconds. In other words, a signal sent into one end emerges from the other end 7 microseconds later.

Now, 100 meters of line is a lot of line to include in a circuit to provide a time delay. However, there is no restriction preventing us from building an *artificial* line. This is just what its name implies, as the following example shows. Suppose we build a coil having an inductance of 50 microhenries, and to this we connect a 100-μμf capacitor so that the circuit resembles a line section. Obviously, we have reduced the length of the section to the physical size of the components, and for the values specified, this could be quite small. If 100 such artificial sections are placed in cascade with each other, the combinations will provide exactly the same effect as the 100-meter transmission line discussed above. Thus, the artificial line may be used to replace the more conventional line when only time delay is considered.

Constructing a number of sections and connecting them in cascade produces a circuit that is still rather long. If time delay is the only consideration, it seems clear that all we need do to shorten the circuit for a given time lapse, is to increase either L or C, or both, per section, so that the number of sections is reduced. Further, it is not necessary to actually build coils and capacitors for the line. A piece of coaxial cable, for example, has sufficient capacitance between

its inner and outer conductors to be of use, but unfortunately, the inductance is too small. This is remedied by winding the center conductor in a very tight helix around a small core, thereby increasing the inductance to the point where practical values of time delay may be achieved in relatively short lengths of line. Practical delay lines of this type provide up to several microseconds of delay per meter of length. For delays greater than a few microseconds, it is still necessary to use the artificial line, since both L and C may be made larger.

Chapter 12

MACHINE AND TAPE OPERATIONS

As previous chapters have shown, both the Ampex and RCA recorders contain a multiplicity of controls. These are necessary to ensure that each subassembly is operating properly, and they are located at the subassembly in which they are used. In most instances, adjustment of these controls is required only at periodic intervals, although a few are usually checked just prior to using the machine. The operator's manual supplied with the machine specifies the correct settings for each control.

Certain other controls, known as *operating controls*, must be available for use at any time, and for convenience, they are grouped together on a control panel. The most obvious operating controls are, of course, the start, stop, record, playback, and fast-speed controls. As a further convenience, control panels of both machines contain meters to indicate circuit conditions that may require attention during operation, together with a few controls needed to make any necessary corrections. Barring an emergency (a defective circuit) the entire machine may be operated from the control panel, or from a similar panel located at a remote position. The switches and push-buttons that control the machine operations generally actuate relays which then perform the switching functions in the various circuits. Thus, during playback, relays disconnect the recording circuits from the heads, energize the playback circuits, switch the servo system connections, and apply power to the reel motors. Use of relay-operated controls also permits special control systems to be tied in to the machine, so that one machine may be turned on and another off at a predetermined time. This latter feature is used by the networks for time-zone delay broadcasting.

Actual operation of either machine consists of loading tape onto the tape deck, checking the various meters and switches to be sure they are correct, and pushing the appropriate button to place the machine in the desired mode of

operation. During operation, both in record and playback, the video monitor and the meters should be observed so that any defect may be quickly remedied.

In the two sections that follow, the various controls and meters available on the control panels are discussed, and their functions specified. Each control has

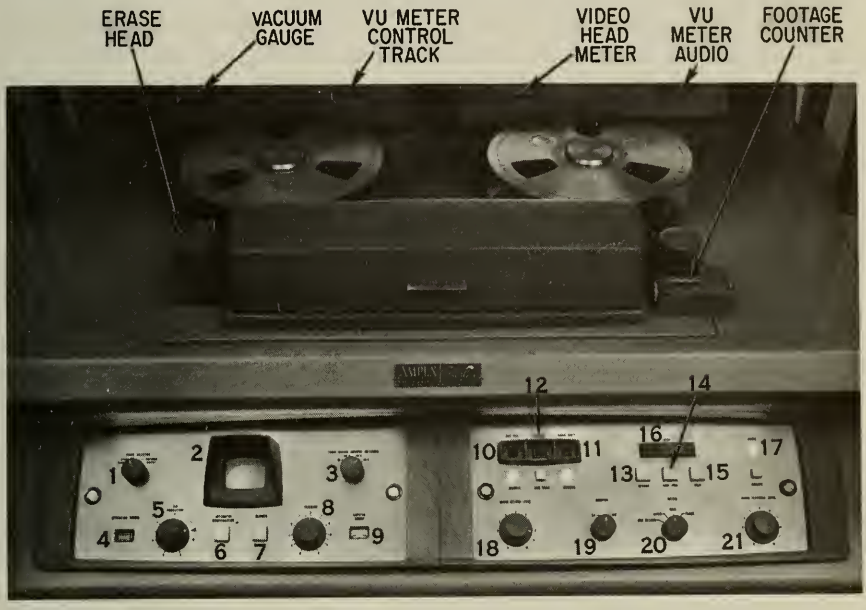


Fig. 12-1. Control panels of the Ampex VIDEOTAPE television recorder. *Courtesy Ampex Corp.*

been numbered to provide simple correlation between the descriptions and the panel photographs.

Ampex Control Panels

The Ampex VIDEOTAPE recorder is operated from a pair of control panels located on the sloping front of the console unit. Two additional panels just to the rear of the tape deck, contain several meters for checking operations. Figure 12-1 illustrates all 4 panels in their relative positions, as seen from the front of the machine. The panels are named in accordance with their position and contents. The panel at the upper left is therefore known as the *left-hand meter panel*, while that to the right is the *right-hand meter panel*. The two control panels at the bottom are also labeled *left* and *right*.

The left-hand meter panel of the Ampex machine contains two meters, a vu

meter for checking the control-track level, and a vacuum gauge for the suction system used in the head-wheel assembly. The right-hand meter panel also contains two meters, a video-recording level meter, used to check the head currents in any one of the four rotating heads, and another vu meter for use with the audio system in either record or playback. For stereophonic sound systems, an extra vu meter is added to the right-hand panel.

The left-hand control panel contains switches, pilot lights, and meters that are used with the servo systems. As indicated in the photograph, these are:

1. OSCILLOSCOPE DISPLAY SELECTOR: This switch selects either of two possible displays, "servo stability", or "head output", and feeds the appropriate signals to the oscilloscope.
2. OSCILLOSCOPE: Used to check the servo-system operation or the head outputs. The screen is of 3-inch diameter.
3. VIDEO RECORD-METER SWITCH: Selects the recording current of any one of the four heads, and feeds it to the head-current meter on the right-hand meter panel.
4. RUNNING-TIME METER: Indicates the total elapsed time the machine has been in either record or playback. In other words, the meter keeps a running total of the number of hours the heads have been in use. It does not operate in the fast forward or reverse modes.
5. TIP-PROJECTION CONTROL: This is used to adjust the position of the concave vacuum guide on the tape deck when the automatic-compensation sensor is in the manual position. The control is continuously variable so that the guide may be moved in either direction. Normal operation is near the center.
6. AUTOMATIC-COMPENSATION SWITCH: A push-pull type of switch that permits selection of either automatic or manual operations for the shoe-servo system. If automatic operation is in use, a light inside the switch head appears brightly lit. When the machine changes itself from automatic to manual, the light dims appreciably. In the manual position, the light is out.
7. BLOWER PROTECTIVE LIGHT: A push-button type switch containing a light inside its head. When the button is depressed, the light glows if the air stream from the blower is present. Conversely, if the blower is not operating, depressing the button provides no light at all.
8. TRACKING CONTROL: Used with the control-track and capstan-servo system, this control may be adjusted to make the heads ride directly over the transversely-recorded video tracks during playback.
9. CAPSTAN-SERVO METER: Reads the control-track signal in either record or playback.

The right-hand control panel contains all the controls necessary for erasing, recording, or playing back the audio track, as well as some additional controls for the tape modes. These controls are:

10. CUE-ONLY SELECTOR: Permits operation of the machine for cueing only.

Video playback is provided in this mode, and the cue record circuits are energized.

11. AUDIO-ONLY SELECTOR: Permits operation of the machine for audio recording or playback. When the machine is operated in this mode, the video heads and the tape guide are not used.
12. RECORD BUTTON: Depressing the button places the machine in the record mode.
13. REWIND BUTTON: When depressed, it causes the tape to rewind.
14. FAST-FORWARD BUTTON: When depressed, it causes the tape to run through the machine at high speed.
15. PLAYBACK BUTTON: This, when depressed, places the machine in the playback mode.
16. STOP BAR: Regardless of operating mode, pushing this bar applies the brakes, disconnects the reel motors from their power source, and stops all tape motion completely.
17. LOCAL OR REMOTE OPERATION: Depending upon which is pushed, these two buttons select the desired operation. For local operation, the button on the left is depressed.
18. AUDIO-RECORD LEVEL CONTROL: Adjusts the level of the audio signal being recorded.
19. MONITOR SELECTOR: Selects either the playback or the recording signal for display on a TV monitor.
20. AUDIO-METER SWITCH: Selects either the record or playback audio signal for display on the audio vu meter.
21. AUDIO-PLAYBACK LEVEL CONTROL: Adjusts the level of the audio signal during playback.

In normal operation of the Ampex machine, only the five tape-mode push-buttons, and the two audio-level controls are required. All other items on the panels are either adjustments made prior to recording or playback, or testing facilities used as a running check on the machine during actual operation. Pilot lights inside the tape-mode push-buttons are activated when a button is depressed, thereby providing instant information as to the mode of operation being used.

RCA Control Panel

The RCA television tape recorder is operated from a single control panel mounted to the right of the tape transport in the equipment. A similar panel at a remote location may be used to operate the machine if desired. All necessary operating controls are located on the panel, as indicated in Fig. 12-2.

1. ON-THE-AIR LIGHT: Turned on when the machine is tied in to a signal source during record, or during playback.
2. CONTROL-TRACK METER: Indicates the control-track head current in the record mode.

3. VIDEO-HEAD RECORD METER: Reads the recording current in any one or all of the four video heads.
4. AUDIO-CUE VU METER: Reads the level of the audio or cue circuits in either record or playback, or the audio or cue erase currents.
5. MASTER-ERASE CURRENT METER: Reads the current in the 2-inch wide master-erase head.
6. AUTO-MANUAL SHOE-SERVO SWITCH: Selects the desired mode of operation for the shoe-servo system during playback only. A pair of pilot lights associated with the switch indicates the mode in use.
7. SHOE-POSITION CONTROL: Provides adjustment of the shoe position.
8. VIDEO-METER SELECTOR: Selects the head current to be read by meter No. 3.

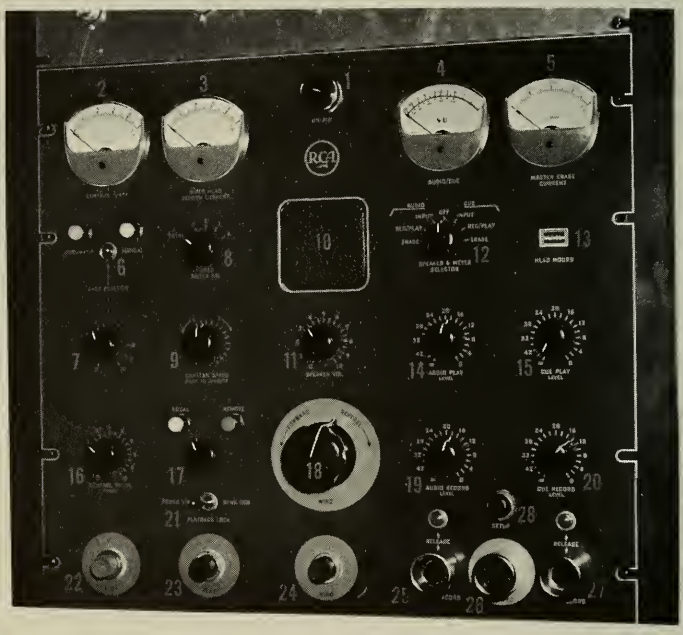


Fig. 12-2. Control panel of the RCA television tape recorder. *Courtesy RCA.*

9. CAPSTAN-SPEED CONTROL: Permits speeding up or slowing down the capstan momentarily, for tracking purposes. The knob must first be depressed before it will operate. Rotation counterclockwise slows the capstan motor, clockwise rotation increases the motor speed.
10. LOUDSPEAKER: Used for monitoring either the audio or the cue track.
11. SPEAKER-VOLUME CONTROL: Adjusts the sound level from the speaker without altering the recording or playback levels.

12. AUDIO-CUE SELECTOR: Positions to the left, control signals fed to the speaker, or to vu meter No. 4 for the audio system. Positions on the right, duplicate these functions for the cue system.
13. HEAD-HOURS METER: Indicates the accumulated running time for the video heads.
14. AUDIO-PLAY LEVEL: Controls the level of the audio playback.
15. CUE-PLAYBACK LEVEL: Controls the level of the cue system in playback.
16. CONTROL-TRACK PHASE: Adjusts the phase of the control-track signal to ensure proper tracking. It is a dual control with concentric knobs providing both a coarse and fine adjustment.
17. LOCAL-REMOTE SWITCH: Selects the controlling position for operating the machine. A pair of pilot lights indicates which panel is in use.
18. WIND CONTROL: When the machine is in either fast mode, this knob controls the speed of the tape from reel to reel. Rotation counterclockwise increases the speed in reverse. Rotation clockwise increases the forward speed. If the knob is placed in the center of its rotation, the tape reels are stationary.
19. AUDIO-RECORD LEVEL CONTROL: Adjusts the recording level of the audio system.
20. CUE-RECORD LEVEL: Adjusts the recording level of the cue system.
21. PLAYBACK LOCK SWITCH: Permits timing the machine to a sync generator, or to the 60-cps line during playback.
22. STOP BUTTON: Depressing the button stops the machine.
23. PLAY BUTTON: When depressed, starts tape through the machine and energizes the playback circuits.
24. WIND BUTTON: When depressed, this button activates the reel motor circuits and allows the wind knob to control the tape motion.
25. AUDIO RECORD BUTTON: When depressed (after machine is first placed in the playback mode) this permits recording on the audio track while everything else is in the playback mode. An unlocking button (above the main button), when depressed, restores the audio circuits to the playback mode. Alternate use of the two buttons permits small segments to be added to the audio track when desired.
26. RECORD BUTTON: When depressed, this button places the machine in the record mode by energizing the video-recording circuits.
27. CUE-RECORD BUTTON: Similar to button No. 25, but operates the cue system only.
28. SET-UP BUTTON: Locks the machine in the record mode without moving the tape, permitting preliminary adjustments to be made.

On a separate panel (Fig. 12-3), the RCA machine incorporates an oscilloscope with a 5-inch diameter screen. A row of push-buttons along the bottom of this panel selects the signals to be displayed on both the oscilloscope and the standard TV monitor, which is located in another rack. The usual controls for intensity, focus, vertical size, horizontal size, and centering, are provided on the

oscilloscope panel. An additional control permits selecting an internal time base of 60, 240, or 15,750 cps, for use with the various displays. By depressing the appropriate button, video input or output may be displayed on the oscilloscope. Other buttons allow the control-track signal or the switcher output to be shown. A few blank buttons are provided for permanently wiring other signals into the oscilloscope, if desired. Depressing any button automatically selects the correct sweep speed for the display. Also, to permit checking amplitude directly,

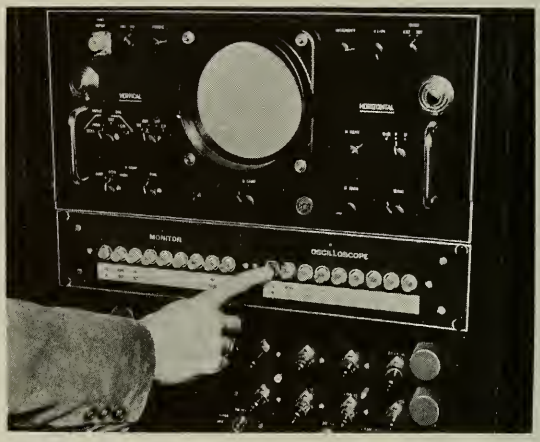


Fig. 12-3. RCA waveform monitor. *Courtesy RCA.*

a calibrating voltage is built into the unit. To make the scope more useful, an input jack at the top left allows signals from any point in the equipment to be fed in for testing purposes. The second group of buttons (to the right) selects the monitor display, color or monochrome, input or output.

Automatic Time-Zone Operations

In April 1958 the National Broadcasting Company inaugurated a system of time-zone delayed broadcasting that permitted programs seen in the East at any given time to be seen throughout the country either at the same *local time*, or, at worst, with no more than a one hour difference. To provide identical time slots for all local broadcasts is possible, but impractical. Instead, the system provides a one hour delay and a three hour delay. Programs delayed by one hour are seen in the Central-time zone at the same local time as the eastern seaboard. Mountain-zone and Pacific-zone stations receive the program after a three hour delay. Thus, a program that starts at 8 PM in New York is seen at 8 PM in Chicago, 7 PM in Omaha, 8 PM in Los Angeles, and 7 PM in Seattle.

Essentially, the system records the program as it is being broadcast on the east coast, rewinds the tape and then plays it back at a later time for the other time zones. The sequence of operations is completely automatic, but may be altered by an operator if necessary.

Although TV tape machines are capable of recording for a full hour, it is obvious that if a machine were permitted to record the east coast program for the full period, there would be insufficient time to rewind the tape before the

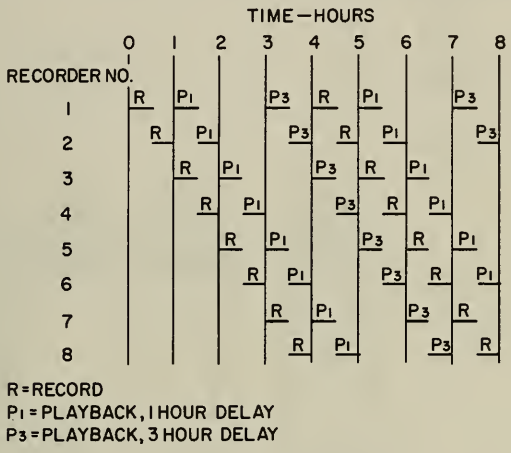


Fig. 12-4. Time stagger chart. Record-playback cycle for one- and three-hour delayed broadcasting. *Courtesy NBC.*

machine would have to start feeding signals back into the network for the one-hour delayed broadcast, since this starts as soon as the program in the east ends. For this reason, each machine is permitted to record for only half an hour. After recording, the machine rewinds itself and waits during the next half hour. At the start of the third half hour, the machine is started up again, and plays back its recorded signal to the one-hour delay stations. At the completion of the half-hour playback, the machine once again rewinds itself and waits for one and one half hours. It then starts playback for the three-hour delay zone. To cover the full time period of three hours, eight machines are operated in staggered intervals as shown in Fig. 12-4. For protection purposes in the event of machine failure, an additional four machines are available.

Figure 12-5 illustrates the plan of the tape room at the Burbank NBC studios, where the system is installed. Inasmuch as color programs occur at random intervals during the day, all the machines are colorized. The equipment consists of four RCA recorders and eight Ampex machines, the latter with special color conversions made by RCA for this specific application. The quality-control

room at the upper right is used for monitoring all delayed playbacks. In most instances, two recordings of a program are available because, for protection purposes, two machines are used to record the original program. A status panel

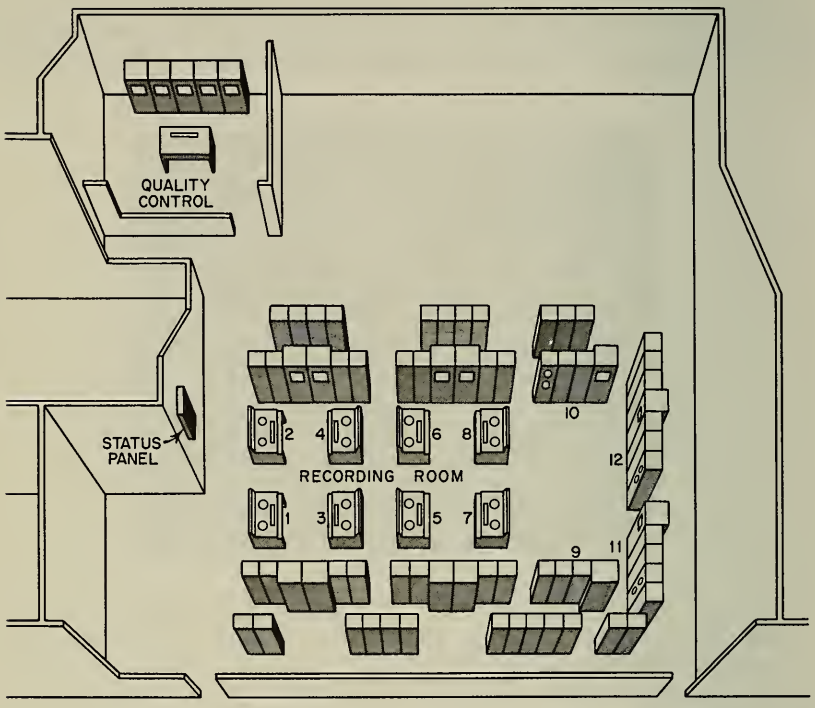


Fig. 12-5. Plan of the tape room at the NBC Burbank (Calif.) studios. *Courtesy NBC.*

at one end of the room indicates the condition of the machines at any time, and permits rearrangement should a machine become inoperative.

Each machine in the tape room may be operated manually (by an operator at the machine itself), or it may be remotely-controlled from any studio in the building. A preselection system is also available. With this system an operator may preset the time at which a given machine is to start operating in either the record or playback modes, and he may also select the video lines to use in either case. When the operation is completed, the machine will rewind itself and wait for additional orders. Finally, each machine may be connected to a delayed-broadcast (db) sequencer that will run the machine through the cyclic modes required for the one- and three-hour delays.

As the machines in use at Burbank are all early models, and lack cue tracks,

each is fitted with special detectors for automatic operation. When a machine is selected to record a network program, tape starts to run through about two minutes before the program commences. At 90 seconds before the program, a 1000-cps tone is recorded on the audio track. The program is then recorded as it comes off the network lines for half an hour, after which a rewind signal is fed to the machine by a clock-operated switch. This signal automatically actuates the necessary relays to cause the machine to stop recording and go into the rewind mode. A detection circuit is connected to the control-track head, and detects the absence of control-track information.

During rewind, of course, the tape is still running over the control-track and audio heads. As the rewinding nears completion, the *start* of the program passes over these heads, and after this, only blank leader, with no recorded tracks whatsoever, runs through the machine. The detector, noting the absence of the control-track signal, activates a relay that automatically throws the machine into the fast-forward mode (not stop), thereby protecting both the brakes and the tape. After two seconds of operation in fast-forward, a second relay changes the mode to playback, and the tape runs through the machine at the normal 15-inch per second speed until the previously recorded 1000-cps tone is detected on the audio track by another special circuit. This special circuit activates still another relay, causing the machine to stop. After it has stopped, the machine waits for a signal from the clock-operated switch that will again start it in motion, and feed the playback signal out over the correct network line. The start signal comes along approximately one half hour later, and starts the one-hour delayed broadcast. At the end of the playback interval (½ hour) another signal from the clock switch once more causes the machine to rewind and cue itself up to the 1000-cps tone. The machine now waits for the next playback signal, which normally comes along after another 1½ hours, thereby starting the three-hour delay broadcast.

Figure 12-6 shows the delayed-broadcast sequencer in highly simplified form. Eight recorders are needed to handle the entire sequence. Stepping switches, mechanically ganged, and operated by pulses from an electric clock, are the heart of the system. The switch moves one step every half hour. The points around the switch correspond to specific machines, as shown, and each deck represents a different operation. In the figure, deck 1 (at the top) is for recording. In the position shown, it causes machine 1 to record signals from the input lines. Half an hour later, when the switch moves one step, machine 2 will be placed in the record mode and machine 1 disconnected from deck 1. The sequence will continue each half hour, with a different machine placed in the record mode at each step.

Deck 2 of the switch provides the automatic rewind signal. As illustrated, machine 2 is in the rewind mode. Actually, the switch only starts the rewind process, for near its end, the control-track and audio-track signals reset the machine and bring it up to the ready, or cue, position.

Deck 3 is the three-hour delay section of the switch. In the Burbank instal-

lation, when machine 1 is recording, machine 3 is playing back the three-hour delay, and machine 7 is playing back the one-hour delay. Deck 4 provides the same rewind signal as deck 2; deck 5 selects machines for a two-hour delay if this is required; deck 6 also provides rewind signals; deck 7 sets the one-hour delayed playback in operation, and, finally, deck 8 is another rewind section. If the two-hour delay is not required, the delay switch at the left may be left open and this sequence is then omitted. For simplicity, the input and output switching circuits, and the system that permits any recorder to be assigned any position in the sequence, have not been shown.

Mobile Operations

Television stations have used mobile installations for many years. In practice, a mobile TV unit is a bus, truck, or trailer in which a sync generator, monitors and video switchers have been installed. Provision for mounting cameras on the roof, are part of the unit. If available, cable is used to transmit the picture back to the studio, but since cable facilities are not likely to be found at every location, a microwave relay is most often employed.

Recently, both Ampex and RCA have made available mobile units that contain TV tape recorders. Instead of sending the signals back to the station, these units record the scene directly on tape regardless of where they happen to be. Each mobile unit is completely self-contained, including a primary source of power (a motor generator) for the equipment.

For news coverage, the mobile unit is ideal, since it can record events occurring at inopportune times, thereby permitting them to be shown at a later hour. The units may also be used in the production of commercials or other programs. In either of these latter applications, the immediate playback available with the tape is a decided advantage, inasmuch as all scenes shot on location may be perfected before moving on.

Tape Copies

An original TV tape recording is a very valuable item, for it stores the performance or event as it actually appeared. If changes are to be made, or if the tape is to be edited, care must be taken not to damage the original, for it cannot be replaced. To protect the original, therefore, editing is usually done on a copy. In tape recording, a copy of an original is known as a *second-generation,* or *first copy* tape. Copies of a copy are known as *third-generation* tapes. The original is, of course, the first generation. Copies are sometimes known as "dubbed" tapes, but this terminology is not often used in television recording. Frequently, too, a complete program may be made up from separate tapes recorded at different times or at different locations. The individual tapes recorded directly from cameras or network lines are then called, for obvious reasons, "originals," while the final edited version is known as a "master."

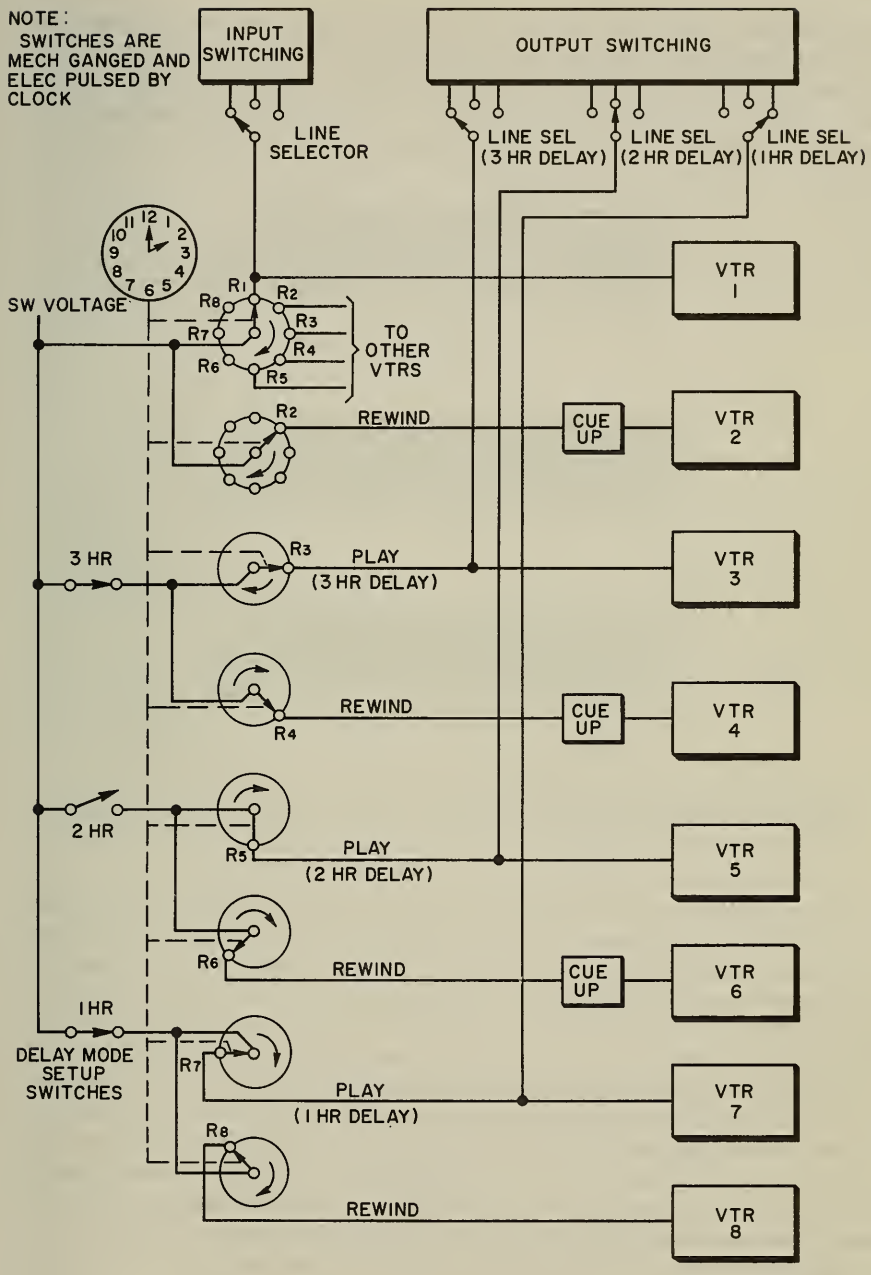


Fig. 12-6. Delayed-broadcasting sequencer operations. *Courtesy NBC.*

At the present time, second-generation tapes cannot be manufactured like motion-picture prints. To obtain a copy, the master must be played back through a standard machine and the output fed into another machine operating in the record mode. Theoretically, there is no limit to the number of machines that may be fed with the same signal simultaneously, but due to the high cost of the

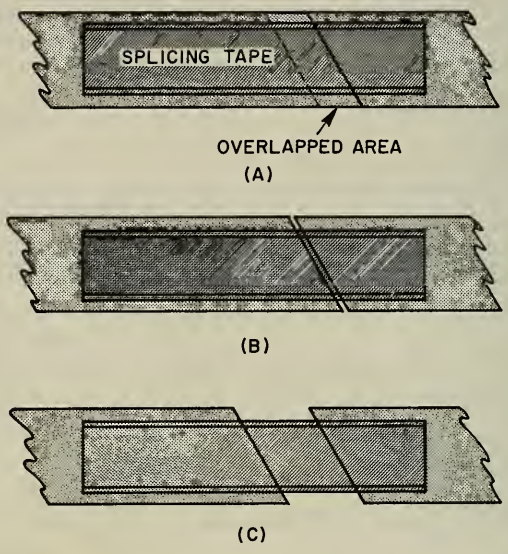


Fig. 12-7. Illustration of splicing technique: (A) overlap (incorrect); (B) butted (correct); and (C) open (incorrect).

machines, only a few are available at any one location. Thus, if many copies are required, the master must be played back quite a few times, or, if this is not considered advisable, third-generation tapes may be made from the copies. In any event, making copies is a time consuming job, for the machines cannot be speeded up.

Generally, second-generation tapes are practically as good as the original, although there may be a slight degradation of picture quality. Third-generation tapes are degraded even further, and provide resolution roughly the equivalent of 16-mm motion pictures. An improvement may be obtained if the playback signal from the original tape is not demodulated when copies are being made, but is instead fed directly to the copying machine as an f-m signal, thereby eliminating any losses in the modulators, demodulators, and sync restorers.

A copy, if complete, contains both the audio and cue tracks, as well as picture information. The control track, however, is not copied, for each copying machine records its own control signals. Under these conditions, a second-

or third-generation tape will be correctly played back, since the new control-track signals will accurately regulate the playback speed to the value used in the recorder making the copy, rather than to the speed of the original, which may be slightly different.

Protection tapes are somewhat different from copies as they are usually first generation. It is common practice at the TV networks to record the video signals on two machines simultaneously. In the event one machine becomes defective during a program, the other machine still operates and provides a recording If both machines operate correctly, one of the recorded tapes is stored away as a protection in case of damage to the other, which may then be used for making copies.

Tape Splicing

In audio-tape recording, musical selections recorded at different times and places are often put on the same tape reel. This is done by joining the end of the tape on which one selection is recorded to the start of the tape containing the next selection. The junction of the two is called a *splice.* Tape splices differ from those used in motion pictures in that there is no overlap of the tape as there is with the film. Instead, the tape ends are *butted* together, as shown in Fig. 12-7, part (B), so that ends of the tape pieces just touch each other. A piece of very light and thin adhesive tape, known as splicing tape, is then applied to the plastic (*uncoated*) side of both pieces at the junction, and pressed firmly into place. The splicing tape holds the two ends together.

Failure to butt the two ends under a splice can cause a momentary loss of signal, since there will be nothing recorded on the splicing tape. If the gap left between the tape ends is relatively wide, there is also a possibility that the splicing tape may adhere to the adjacent layer of tape in a reel. In turn, when the tape is run through a machine the pull on the tape as it tries to feed into the head assembly and is resisted by the adhesion of the splicing tape, may cause the splice to come apart. It is also possible for the splicing tape to adhere to the capstan or pinch-roller, causing tape to jam up at the heads, or to snap off at the splice. Conversely, if the tape ends are overlapped and playback is attempted, the overlapped portion may cause the tape to jam in the machine, or it may pull apart at the splice since, in effect, one end of the tape under the splice is hanging loose. If the splicing tape is applied to the coated side of the tape there is a decrease in signal amplitude when the splice runs through the machine, for the splicing tape, thin though it may be, forces the oxide coating away from the necessary intimate contact with the heads.

There are many devices and machines used for splicing tape of all widths. The simplest, and perhaps the most effective, is the EDITALL splicer, illustrated in Fig. 12-8. The long, curved, groove running through the splicer is designed to hold the tape by the edges without any need for pads or weights. The unit is available in various sizes to accommodate any width tape up to 2 inches.

To use this type of splicer, both ends of the tape to be spliced are placed in the slot, coated side down. Either end may be moved with slight finger pressure. To ensure a perfect butt splice, the ends to be joined are overlapped slightly at one of the vertical slits, and a cut is made through both pieces with a razor blade. The small loose ends are discarded, and splicing tape is applied to the junction and rubbed firmly into place. The splicing tape used should be just

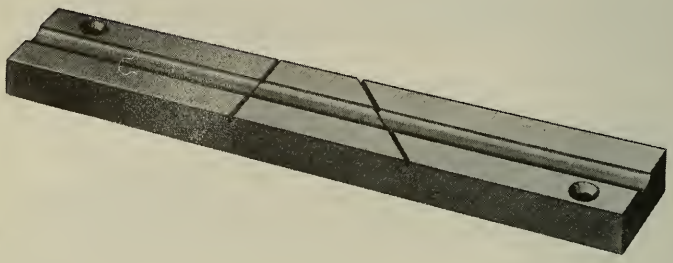
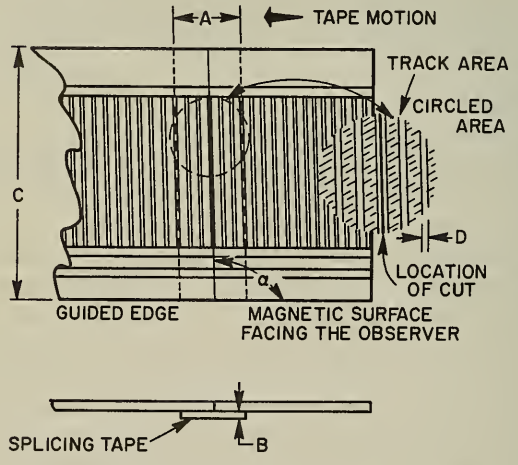


Fig. 12-8. The EDITALL splicer. *Courtesy Tech Laboratories, Inc.*



Note: Drawing is not to scale.

Dimension		Inches
A	Width of splicing tape	0.25 nom.
B	Thickness of splicing tape	0.0007 max.
C	Width of magnetic tape	2.0 nom.
D	Distance between recorded tracks	0.0056 nom.
α	Angle of cut	90° 33′ ± 3′

Fig. 12-9. Television tape splice.

slightly smaller in width than the tape itself, so that it does not protrude past the tape edges and cause a jam-up in the machine.

If the butting ends are at right angles to the tape edges there will be a very rapid transition of output when the splice passes the playback head. A somewhat slower transition is afforded by cutting the tape at an angle. For audio recording where a gradual blending of sounds from one tape to another is de-

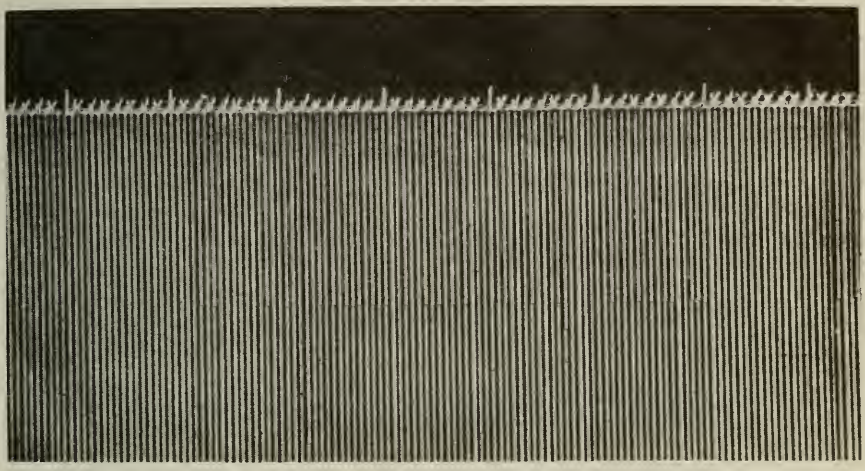


Fig. 12-10. Field pulse on recorded tape. *Courtesy NBC.*

sired, the cut across the tape may be made at a very small angle to the edge. Such a cut may require several inches or more of tape length, but this is not too difficult to achieve.

When a previously recorded audio tape breaks, the splice is made without further cuts if it is at all possible. Since the ends to be joined will have matching configurations, they are merely butted together, and splicing tape applied. This prevents the occurrence of signal drop-outs due to a part of the tape being removed to effect the splice.

Television tape may be spliced in the same manner as audio tape. There is, however, one difference. A splice should be invisible to the viewer, so for this reason, TV tape splices should be made during the vertical blanking interval. To prevent loss of vertical blanking signals, the splice is made by cutting the tape through the center of the guard band between adjacent tracks on which vertical blanking has been recorded. Since the tracks have a pitch of only 15.6 mils, the cut is almost at right angles to the tape edges, as illustrated in Fig. 12-9. The splicing tape used in video applications is quite thin, and is made narrow in the longitudinal direction to prevent any possible timing errors or

jumps when the splice passes over the video heads. In practice, video splicing tape is ¼-inch wide and 0.0007-inch thick.

In order to splice two pieces of television tape together, it is first necessary to locate the blanking interval. This is easily done by applying an editing fluid to the coated side of the tape. The fluid contains carbonyl, or finely suspended, iron particles that adhere to the tape wherever recorded signals appear. The vertical blanking interval may then be identified, and a cut made in the adjacent

Fig. 12-11. Editing pen and fluid. *Courtesy Ampex Corp.*

guard band. In practice, the editing fluid is applied only to the lower edge of the tape, where the control track appears. The 60-cps field pulses recorded on this track are used to identify the correct splicing position, as shown in Fig. 12-10. Note that the pulse itself appears at the edge, rather than in the center of the recorded track.

The editing pen shown in Fig. 12-11 is useful in working with TV tape. The body of the pen is filled with the fluid, and the felt writing tip applies this to the tape wherever desired. A piece of felt soaked in the fluid may also be used to locate the field pulses.

After both pieces of tape to be joined have been properly cut, they are butted together and the splicing tape applied. Any residual iron particles from the editing fluid must now be wiped from the tape, if this was not done previously. Failure to wipe the tape clean may permit the particles to fall into the gaps of the heads, thereby short-circuiting the magnetic path across the gap.

Ampex has made available a jig (Fig. 12-12, A through G), that performs the splicing functions quite easily. After the tape edge has been developed by the editing fluid, a rough cut is made just beyond the blanking interval. The two pieces to be joined are inserted in the jig, coated side up, so that the field pulses are visible. The top of the jig is essentially a pair of special clamps that

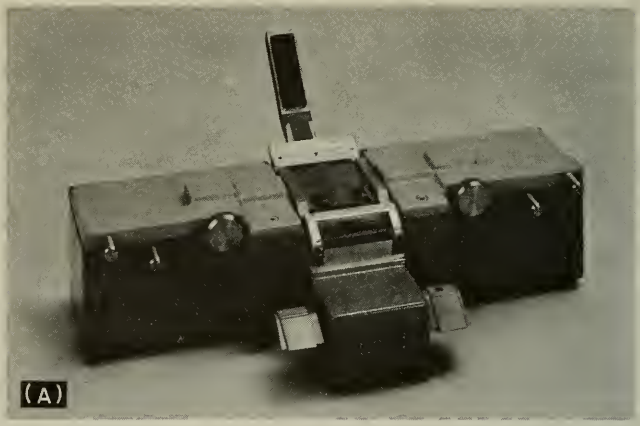
hold both pieces of tape firmly. Each clamp is movable, and the knobs controlling the motion, and therefore the position of the tape in the jig, are adjusted, until the field pulses are aligned with special markings on the edge of the jig. A razor blade is then used to cut the tape at the correct location, assuring a perfect butt splice. The center-section clamps and tape are next lifted up, and splicing tape drawn through the jig, after which the tape is again lowered into place, forcing the splicing tape against the butted ends. A pressure block is then used to ensure adhesion of the splicing tape to the recorded tape. Since the tape is placed in the jig coated side up, the splicing tape appears on the polished, or back side of the tape, where it belongs.

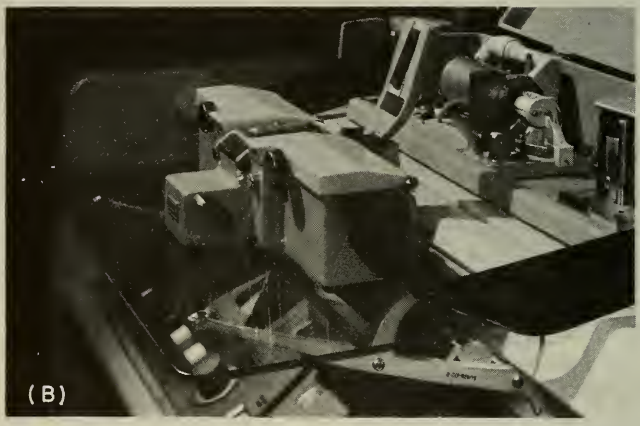
When a correctly spliced tape is run through a machine in the playback mode, the splice itself is not noticeable. However, if the two pieces that were joined were recorded on different machines, or at different times, the head-to-tape pressure required for correct sync timing may be different. If this is the case, a venetian-blind effect may be noticed in the picture immediately after the splice has run through. The effect disappears as soon as the shoe servo corrects for the error, or, if the shoe is operated manually, as soon as the operator adjusts the shoe pressure. In the event the edges of the splice are not butted together correctly, the recorded tracks on the second section will not fall directly under the video heads, causing a loss of signal and increase in noise. The tracking control of the capstan servo may be used to pull the tape into position when such a condition is noticed. It should be noted that splicing two odd fields or two even fields together, does not cause difficulty, since monitors and TV receivers compensate for this very rapidly.

Tape Editing

One of the many advantages accruing from the use of tape in TV program production is the availability of immediate playback, a feature that permits a director or producer to shoot a scene over and over again until he is satisfied. However, at the end of a shooting session, the reel of tape on the machine may contain several "takes", or versions, of each scene recorded at the session. It then becomes necessary to cut-out the unwanted versions and join together the desired recordings of the various scenes to make up the full program. In some instances, tape that was recorded previously, a commercial, for example, has to be inserted at an appropriate point. The process of assembling a final recorded tape from all the takes is known as *editing*. Inasmuch as we have already discussed the technique of splicing, we need now only concern ourselves with the methods of identifying scenes, and locating the position on the tape where a cut is to be made. There are several editing methods in use, and these are described below.

The simplest method of editing is used mostly for the removal of bad takes from a reel. The tape is run through the machine and viewed on a monitor. When the start of the undesired section appears, the machine is stopped, and





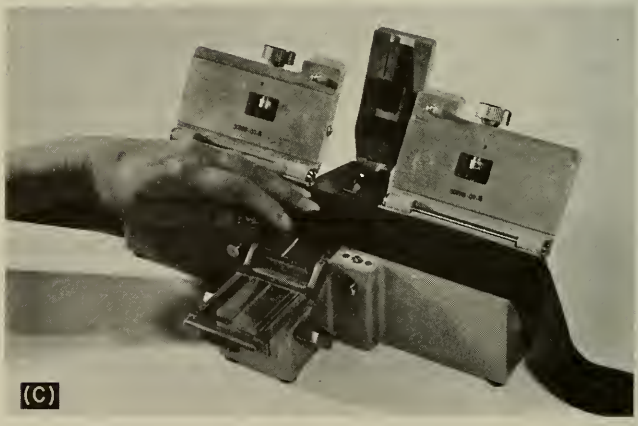
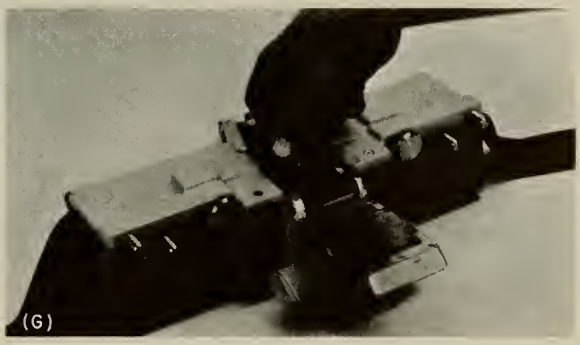


Fig. 12-12. (A) Ampex editing jig. (B) The jig in position at the front of the Ampex VIDEOTAPE television recorder. (C) through (G) Steps in making a splice. *Courtesy Ampex Corp.*

(D)

(E)

(F)


(G)

the tape backed up several inches to compensate for that which ran through between the observation on the monitor and actual stopping of the machine. The nearest field pulse is then located as described previously and the tape cut. The undesired section may then be run through the machine and wound onto an empty reel until the end is reached, at which time the tape is again cut at a field pulse, and the remainder spliced back to the preceding usable sections.

One method of locating a scene is to utilize the cue track. For instance, when several takes appear on a single reel, the producer or director may examine them on the video monitor. During this playback the cue-track recording circuits are turned on, and specific instructions as to editing are incorporated onto the tape. Spoken cues such as these are usually insufficient to locate the exact start or end of a scene; they are mainly useful for giving rough indications of what is wanted.

Another method uses the recorded audio track as a cutting guide. With this method, the tape is taken off the machine and placed in a fixture containing only audio heads and reel motors. The tape runs through the fixture until the operator hears the start of the sound. He then stops the machine, and "rocks" the tape back and forth across the audio head by hand, until the exact starting

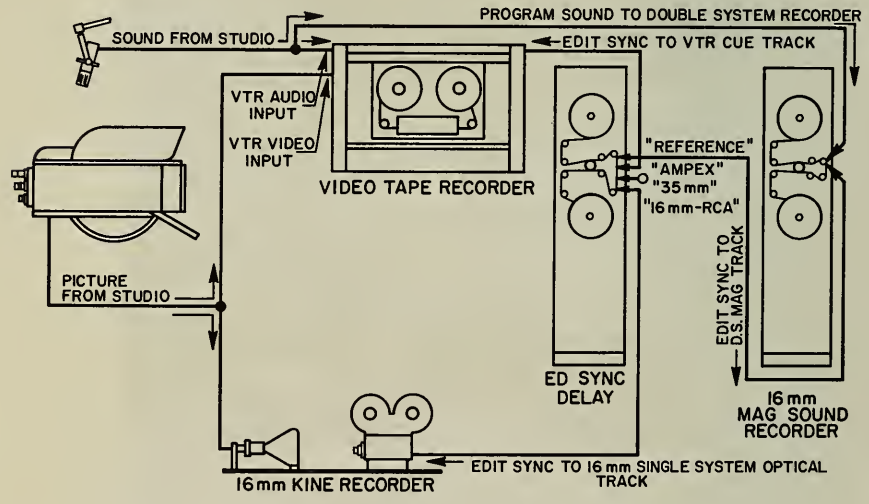


Fig. 12-13. Double-system editing layout. *Courtesy NBC.*

point has been found. The tape may be cut at this point, or, if tight picture editing is desired, 9 inches further along, up the tape, since the sound leads the picture by this amount. The end of the sound is located in a similar manner, but at this point the cut *must be made* 9 inches up the tape to avoid losing the last 18 frames of picture. If the start of the section is cut at the 9-inch point,

surprisingly little sound is lost, for the time required for the 9 inches to run through is just slightly more than one half second. In some instances, sound is deliberately not recorded at the instant the picture starts, in which case the editor, relying on information on the cue track, hunts for the start of the picture after locating the start of the sound. The editing fluid is used to locate the beginning of the full track pattern, which is the start of the picture.

A more elaborate arrangement, known as "double-system" editing, is used by NBC. As Fig. 12-13 illustrates, video signals from the studio are sent to

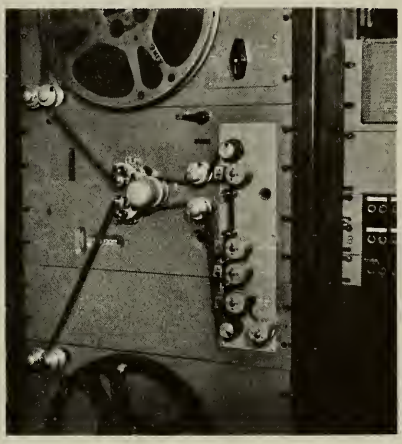


Fig. 12-14. The edit-sync delayer. *Courtesy NBC.*

both a TV tape recorder and a 16-mm kinescope recorder. The sound is also recorded twice, on the television tape recorder, and on a separate sound recorder. An "edit-sync" signal, consisting of short "beeps" (bursts of 3000-cps tone) exactly one second apart, is also recorded on the television tape (on the cue track), the kinescope film sound track, and the additional sound recorder. Each beep is identified by a voice count. The edit-sync signal, obtained from a previously recorded master tape one hour long, is run through a special playback machine (shown in detail in Fig. 12-14) whenever a TV tape recording is made. Separate heads are used for the output to the video recorder, the kinescope recorder, and the sound recorder, causing the beep to arrive at the various machines at delayed intervals. This is done to ensure that the beep will appear at the same physical point on all the recordings, since tape and film speeds, as well as sound head positions, differ on the various machines used.

After the recordings have been made, the kinescope film, or "work print", is used to edit the material. The optical image produced by the film provides a method for precisely locating points to be cut without any damage to the tape, or loss of a recorded section. When the work print has been edited, the edit-sync pulses permit the tape to be cut at identical points. The tape is cut, of

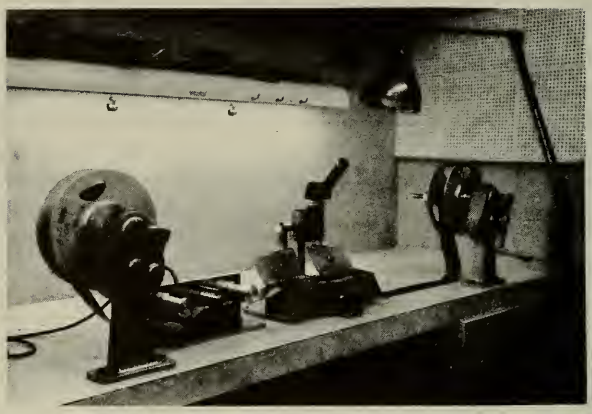


Fig. 12-15. Editing bench. *Courtesy NBC.*

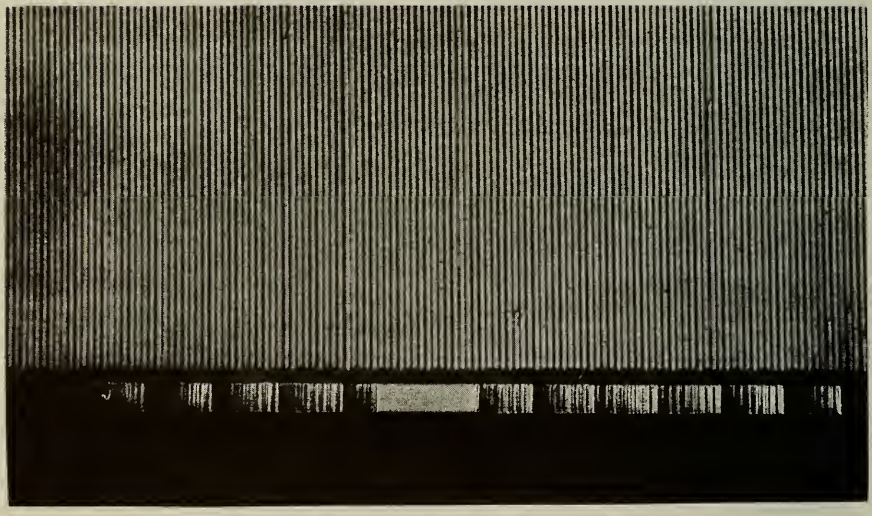


Fig. 12-16. Edit-sync pulse. *Courtesy NBC.*

course, at the appropriate field pulse. In practice, the tape itself is edited on a special bench, shown in Fig. 12-15, which permits the edit-sync beep to be monitored. Figure 12-16 illustrates the position of the edit-sync beep along the tape.

After the video portions of the tape have been assembled into a complete program by the foregoing method, the sound track from the extra sound recorder is tailored to fit the picture. Again, the edit-sync pulses are used to locate the necessary sections on the sound track. If desired, sound effects — applause, music, etc., — may be added, and a final composite track obtained. This is then

recorded on the tape by feeding the sound into the video recorder while it is operating in the "audio only" mode. In this last operation, the sound reproducer and the television tape machine must be accurately synchronized.

A more recent approach to assembling final programs is an electronic editing system. The various takes, previously recorded on tape, are played back simultaneously through a bank of video machines each connected to a separate monitor, and to a TV switcher substantially identical to that used in a live studio for switching from one camera to another. The editor may view all monitors simultaneously and select the take he desires by depressing a button on the switcher. The output of the switcher is sent to another machine where it is re-recorded on tape. The re-recording is continuous, and contains the scenes selected by the editor in their proper sequence. Splices are not required since the switcher effectively does the same job. Further, use of this method permits fades, wipes, dissolves, and other trick effects to be added to a program, although the original scenes may have been recorded without them.

Tape Handling

In the laboratory, simulated environmental tests have indicated that the magnetic properties of video tape are just as stable over long periods of time as sound tape. Unless altered by magnetic means, i.e., stray fields or close proximity to either permanent or electromagnets, the recording is permanent. However, unclean heads on the recorder may damage the oxide surface of the tape, resulting in poor recordings or playbacks. Further, improper handling or storage may contaminate the tape or distort its base material, creating difficulties during playback. If high-quality results are to be achieved, there are certain precautions that should be observed when handling or storing the tape.

The foremost precaution is, of course, to avoid accidental erasure by magnetic fields. Strong fields can erase a tape from several inches away. In fact, this is the principle on which the bulk eraser is constructed. Normally, though, the fields required to erase a recorded tape are so intense that accidental erasure is not likely to occur unless the tape is inadvertently placed near a bulk eraser. D-c fields, in particular, affect virgin tape by saturating it prior to recording, resulting in an increase in the noise level. Weak fields, too, can affect the tape by partially erasing small segments. It is only common sense then, that magnetic latches should not be used on tape storage cabinets. Finally, during operation, parts of the recorder may become magnetized. This also can cause erasure, or it may add a spurious signal to the tape. To prevent such occurrences, the machine should be periodically demagnetized in accordance with the manufacturer's instructions.

When not in use, tapes should be kept covered. After being uniformly wound onto a standard reel, they should be inserted into a dust-proof polyethylene bag which is then placed back into the original box. Each box should be plainly labeled as to contents so that no mistake will be made at a later time

when the tape is needed. Storing the boxes on end will prevent bending or distorting the reel flanges, a necessary precaution, for in use on a machine, bent flanges damage the edge of the tape.

Clean white gloves should be used by editors and others who normally handle tape, to prevent contamination of the oxide coating by body oils and salts.

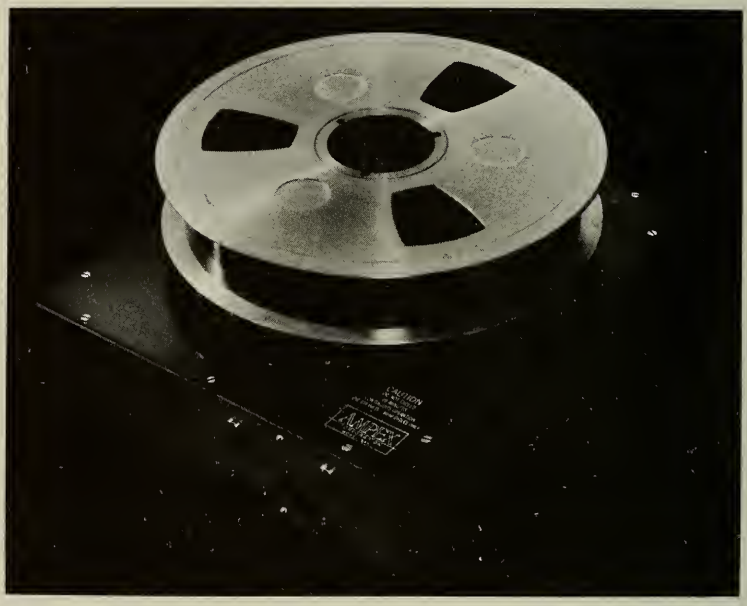


Fig. 12-17. Illustration of a bulk eraser. *Courtesy Ampex Corp.*

Although not essential when loading or unloading the recorder, it is nevertheless a good idea to get into the habit of wearing gloves. As a further preventative against damage to the oxide, it is wise to clean the tape path and heads prior to each use, to remove accumulations of oxide particles and other matter that might damage the tape. Follow the manufacturer's recommendations for such cleaning.

Tapes should be recorded and played back under substantially similar conditions of temperature and humidity. Normally, in a studio this is no problem. Suppose, however, that a tape has been in transit or storage at subzero temperatures. Such low temperatures cause a dimensional change that is cumulative, and the tape, if played back immediately, would be out of synchronization by about 1 track in 10 inches. Before using the tape, then, it should be allowed to stand at room temperature for 4 to 8 hours, although it will not regain its exact dimensions for almost 16 hours. It is possible to shorten the "warm-up" time by raising the ambient temperature, but the tape should never be subjected to temperatures in excess of 100°F, or condensation will form on the coating.

Lamps and other forms of spot heat should not be used to warm up tape. In general, manufacturer recommendation is that video tape be stored and used in rooms in which the humidity is between 40 and 60% and the temperature between 60° and 80°F.

Accessories

The video recorders manufactured by Ampex and RCA are complete in every respect, but their work may be facilitated by the use of several available accessory units. These are listed below.

1. **Bulk Eraser:** Early versions of the Ampex recorder were manufactured without a master-erase head. Thus, in order to re-use a recorded tape it became necessary to provide an erasing method. The bulk eraser of Fig. 12-17 is convenient in this application. The reel of tape is mounted on the unit and rapidly rotated through a strong 60-cps magnetic field. Variations in field strength as the tape rotates effectively wipe it clean. The bulk eraser is also useful with newer machines, for after editing, bad takes may be readily erased without running them through a machine, thereby preventing them from being accidentally spliced into a program. This also eliminates lost time, for the recorder is free for more important work than erasing unwanted takes.

2. **Head Degausser:** The magnetic heads used in the machines eventually acquire a small amount of permanent magnetism. If this is not removed, the frequency response deteriorates and distortion tends to increase. At periodic

Fig. 12-18. A head degausser. *Courtesy Audio Devices, Inc.*

intervals, then, heads should be demagnetized. In fact, it is wise to degauss the heads prior to each recording session, to be on the safe side. This is done very easily with the device illustrated in Fig. 12-18. The unit is turned on, and the tip allowed to touch the head, after which the degausser is moved slowly away from the head for a short distance, and then turned off. The 60-cps field induced in the head is reduced gradually as the degausser is moved away, thereby demagnetizing the head.

3. **Alignment Tape:** Essentially, this is a prerecorded tape made under

exacting laboratory conditions. Ampex provides such a tape which runs for five minutes. The video signal on the tape is the standard "Indian Head" pattern used in most TV studios. A 400-cps tone at 0 dbm appears on the audio track, and the control track contains a field pulse at ¼-inch intervals. The tape is used, of course, to check the proper operation of the various circuits in the machine. The effect of any adjustment is easily noted in the monitor pattern.

4. **Tape Timer:** This unit, manufactured by Ampex, is basically a footage counter, but it is calibrated in units of time. Thus, scene or program lengths may be easily determined. The device operates correctly at high speeds as well as at normal tape speed. The timer may also be used for cueing purposes by backing up the tape on the machine the desired number of seconds.

5. **Remote Control:** Available on both Ampex and RCA machines, this permits major control functions to be handled at a more convenient location instead of directly at the machine.

6. **Ampex "Interswitch":** Available as a modification on the Ampex machines, the interswitch unit permits the machine to record or playback at any one of four TV standards: the 525-line system in use in the U. S., the British 405-line system, and the European 625- and 819-line standards. The selector switch alters the necessary circuits so that head-wheel speed and frequency response are both changed.

7. **RCA Modification:** The RCA machine may also be modified to operate on European standards, except that it is not available for use with 819-line systems. The modification includes the timing counter used for measuring program length. Due to slightly different tape speeds and line frequencies, the internal gearing of this unit must be changed to suit the application.

The Future of Television Tape Recording

Unwise as it is to predict the future, it seems safe to say that television tape is here to stay, and that it will play an increasingly important role in TV, both as a method of recording late-breaking news, and for prerecording shows. Shows seen on local stations via syndicated films will eventually be replaced by syndicated tapes. Government and industry will find many new applications for the machines, and they will perform tasks that are outside what we might consider their normal domain.

A great amount of research is being carried on to provide better recording methods. In line with this, both RCA and Ampex are continuously improving their machines. One of the major drawbacks of the present video recorder is the mechanical tape-scanning system that must be used. The video recorder of the future may well dispense with this, and provide some form of electronic scanning to record and playback the video tracks. Such a machine would provide many thousands of replays instead of the 200 or so, that current machines permit.

One method of electronic scanning, utilizing a somewhat different approach,

has been developed by the General Electric Company. Known as *thermoplastic recording*, the process was originally developed to permit the recording of any type of wideband electrical signal, and has been used experimentally to record video information. Briefly, the system uses a special film that is electronically

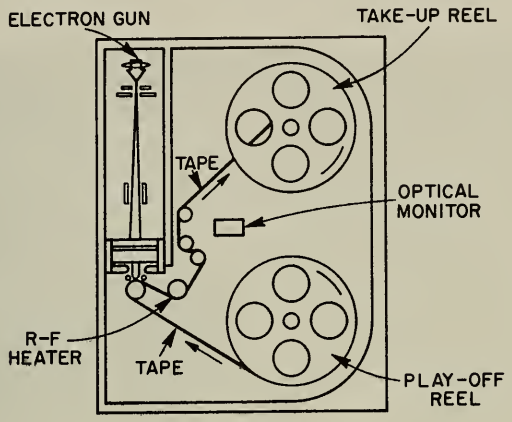


Fig. 12-19. An experimental thermoplastic recorder layout. The film passes under the electron beam to receive its charge, and then through the r-f heater, where deformation occurs. *Courtesy The General Electric Co.*

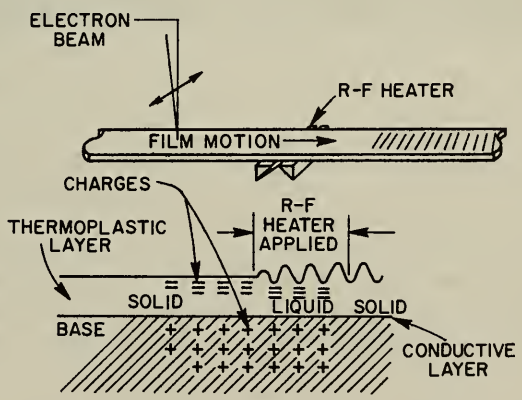


Fig. 12-20. The thermoplastic recording method. The beam at the left lays down the pattern of charges on the film as indicated. When the film is heated, the charges on top and base attract each other and move closer together, deforming the film as shown. The pattern "freezes" on the surface when the heat is removed. *Courtesy The General Electric Co.*

charged by the signal and then deformed by heat, producing ridges and valleys on the film surface proportional to signal amplitude.

Figure 12-19 illustrates the thermoplastic recording process, and Fig. 12-20 shows its mechanical functions. The film consists of three layers, one of which, the base, has a high melting temperature. This is coated with a thin, transparent,

Fig. 12-21. Home-type television tape recorder of the future. *Courtesy RCA.*

conductive layer that is then covered with a low-melting temperature thermoplastic material. The film is unwound from a storage reel, like tape, and passed under an electron beam that is modulated by the signal to be recorded. The signal amplitude controls the amount of electrons in the beam, and these in turn deposit a charge on the surface of the film. Thus, high-signal amplitudes produce high charges on the surface, while low-amplitude signals cause much less charge to be applied. During the recording process the beam is swept across the film much in the manner of the horizontal sweep in a TV receiver, while the constant motion of the film past the beam provides the equivalent of continuous vertical deflection. The recorded charge pattern therefore appears as a continuous raster of horizontal lines across the film somewhat similar to the track pattern shown in Fig. 6-8, but each line is much thinner than a tape track.

After passing under the beam, the film is routed through an r-f heating system. High frequencies generated by the r-f system cause currents to flow through the conductive layer between the base and thermoplastic covering and

heat the film to a temperature sufficient to melt the top, thermoplastic layer. The forces of attraction between the negative charges laid down on the top surface by the beam, and a positive charge on the base, now cause the liquid thermoplastic layer to become deformed by creating depressions wherever a charge appears. The amplitude of the depression is determined by the point at which the electrostatic forces due to the charges are counterbalanced by the surface tension of the liquid thermoplastic. In practice, this means that the amount of depression depends upon the amount of charge which, in turn, is proportional to the signal amplitude. As the film moves on, away from the vicinity of the r-f heater, the heat is dissipated in the base layer and the pattern of depressions "freezes" on the top surface of the film, which may then be wound onto a take-up reel. Melting and deformation can be accomplished in as little time as 10 milliseconds. The entire mechanism is contained within a vacuum chamber to allow operation of the electron gun.

Playback of the recorded signal may be accomplished both optically and electrically. In either case, a special optical system that converts the hill-and-dale recording into varying intensities of light, is required. This can produce images in either black and white or in color. The optical system then projects these variations either onto a screen for direct viewing, or into a camera tube for conversion to a TV signal. A flying-spot scanner and photoelectric cells may also be used for developing a TV signal from the recording. The optical playback arrangement provides an advantage because it makes editing much easier.

As with standard television tape, thermoplastic film may be erased and re-used. This is accomplished by heating the film well above its melting point. The depressions are then removed as the thermoplastic material melts and flows into a smooth layer. By controlled application of rf to the film it is also possible to erase small areas while the bulk of the film retains its signal.

Although the thermoplastic recorder has been demonstrated in the laboratory, it has not yet reached the production stage. In fact, it may be some time before commercial models of this system are available for general use.

RCA is also developing a home-type tape unit (Fig. 12-21) that will attach to a TV receiver, either color or monochrome. The machine is small and compact, and will permit home viewers to enjoy prerecorded tapes rented from a tape library. The television receiver, in conjunction with a good audio tape machine, will then truly become the focal point of home entertainment.

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